UNIVERSITY OF OULU

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MASTER'S THESIS

RADIO COMMUNICATION VIA NEAR VERTICAL INCIDENCE SKYWAVE SYSTEM

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ABSTRACT

While the overall picture of our cutting-edge communication framework is one of high unwavering quality, the practical experience could be completely different during catastrophic situations, when communication services are disrupted due to damages in the communications infrastructure. Moreover, wireless connectivity in remote areas of the works is still a highly significant problem, with an estimated two billion people being outside of the connected world. This thesis studies the use of high frequencies communications as a way to address the above-mentioned cases. High frequency (HF) communication utilizes radio waves between 3 and 30 MHz with the wavelengths of 100 to 10 m. The dominant means of long-distance communication in this band is skywave propagation, in which radio waves that are directed at an angle into the sky are reflected on Earth by the ionized layers of the atmosphere. HF ionospheric reflection technique is commonly used specifically for military, maritime, aeronautical, and emergency communication in remote areas, and as backup system. Factors such as season, sunspot cycle, solar activity, as well as polar aurora plays significant roles in the sustainability of HF radio communications. Propagation plays the most significant role while designing a communication network. Radio waves propagates with an objective of transmitting signal successfully without having an error. So, studies on wave propagation mechanisms, channel and noises are equally important.

This thesis focuses on high frequency near vertical incidence skywave (HF NVIS) technology. NVIS, exploiting a frequency range of 2-10 MHz, can provide continuous coverage up to a couple of hundred kilometres from the transmitter without skip zone. NVIS operation is considered during disaster relief operations when infrastructure is severely damaged or where tactical communication is needed in military operations. NVIS operation requires the presence of substantial ionization in the ionosphere directly above the transmitter. For optimizing a NVIS communication system, the most important parameters to consider are elevation angle, fading, noise and polarization. Furthermore, NVIS operation requires careful selection of antennas, operating frequency, maximum usable frequency (MUF), lowest usable frequency (LUF), as well as frequency of optimum transmission (FOT) for successful communication. At the time of emergency, low data services such as voice and text could be easily established with NVIS system. A comprehensive overview of NVIS based on number of research articles is given which highlights ionospheric propagation, antennas, the operational use of HF communications, as well as applications. Further, we highlight the challenges with possible solutions, and future research direction to ensure NVIS system sustainability. From this literature review, the significant relationship between NVIS antenna and NVIS propagation mechanism is discussed. Furthermore, thesis provides a reference text to understand various elements of NVIS system and demonstrate how modern technology can be used

to solve HF issues. We believe that this article will encourage more interests in addressing the technical challenges on the research and development of future HF radio communication systems.

Key words: High frequency, ionospheric, skywave, NVIS, skip zone.

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FOREWORD

The thesis work is completed at Centre for Wireless Communications research unit at University of Oulu as a partial fulfilment for the completion of master's degree in Wireless Communications Engineering. I am very much thankful to my supervisor on the thesis, Prof. Marcos Katz for his support, comments and reviews during the thesis project. Without your directions, the completion of this work would not be possible. My words of gratitude to the advisor of my thesis, Dr. Kari Karkkainen. Your guidance at each stage made the timely accomplishment of the work possible. The work gave me an insight to the practical implications of the theoretical knowledge I have been familiar with. Finally, I would like to thank Doctoral student Dinesh Acharya for his valuable review and suggestion during the thesis work.

I would like to dedicate this thesis to my parents and my wife for their unconditional love, encouragement, and support.

MD Helal Hossain
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LIST OF ABBREVIATIONS AND SYMBOLS

AI	artificial intelligence
ALE	automatic link establishment
EMC	electromagnetic compatibility
FDM	frequency division multiplexing
FOT	Frequency of optimum transmission
FSK	frequency shift keying
FEC	forward error correction
HF	high frequency
ICT	information and communication technology
IRE	institute of radio engineers
ITU	international telecommunication union
IoT	internet of things
ISI	inter-symbol interference
LOS	line of sight
LUF	lowest usable frequency
MUF	maximum usable frequency
MF	medium frequency
MIMO	multiple input multiple output
NVIS	near vertical incidence skywave
NLOS	non-line of sight
PSK	phase shift keying
PCA	polar cap absorption
QPSK	quadrature phase shift keying
QoS	quality of service
SNR	signal to noise ratio
SISO	single input single output
SDR	software defined radio
SID	sudden ionospheric disturbances
SSN	sunspot number
TDM	time division multiplexing
UHF	ultra-high frequency
UV	ultra-violet
UK	United Kingdom
UN SDGs	United Nations sustainable development goals
VHF	very high frequency
VLSI	very large-scale integration
VLF	very low frequency

KHz	kilo hertz
MHz	mega hertz

km	kilometre
sin	sine
sec	secant
%	percentage
5G	fifth generation mobile phone system
4G	fourth generation mobile phone system
6G	sixth generation mobile phone system

B_o	magnetic field strength
n	refractive index
f	wave frequency
Φ_0	angle of incidence
f_N	plasma frequency
TBR	true path between transmitter and receiver
f_V	vertical incident frequency
h	virtual height
TAR	virtual path between transmitter and receiver

1. INTRODUCTION

Wired as well as wireless communications have been widely exploited for decades. At the present time, the telecommunication sector is highly developed both technically and financially, supporting exchange of information at a global scale. The electromagnetic spectrum contains a range of frequencies that is exploited for wireless communications purposes [1]. The goal of modern communication system for example beyond fifth generation (B5G) and sixth generation (6G) is to identify research areas such that everyone has access to the internet connectivity, especially those in remote and rural areas. High frequency (HF) communication is used for short and long range tactical and strategic military purposes as its antennas and equipment can be positioned quickly to offer immediate contact without the need for careful site preparation, as is the case with line of sight (LOS) communications. HF radio communication is based on the ability of the ionosphere to bend signals back to Earth. Whether a signal may bend back to Earth at the angle required to link two separate locations depends on a variety of variables, including the ability of the ionosphere to bend the signal, the frequency of usage, and the angle at which the signals reach the ionosphere [2], [3], [4]. An angle of incidence is the angle at which the signal enters the ionosphere, relative to a line perpendicular to the ionosphere. Near vertical incidence skywave (NVIS) propagation is defined as providing continuous coverage from nearly 0 Km to a couple of hundred kilometers from the transmitter with no skip zone [5], [6], [7].

In the case of remote areas without telecommunication coverage, one attractive option is satellite connection which, on the other hand, has a high cost. In this situation, one of the best alternatives is HF communications with ionospheric reflection. Militaries, can be taken as an example, relies on the HF technology in distinctive cases for reasons like communication security, redundancy, and effective cost. This thesis focuses on the possibility to sustain NVIS communication by integrating the concept of modern communication approach with NVIS unique characteristics. The resultant structure could be a good candidate for the novel scenarios and applications of medium to long range communication systems. This thesis studies NVIS communication approaches operating in HF band. Considering the ionosphere and various propagations approaches, NVIS system will be discussed from different viewpoints. Based on state-of-the-art, various challenges, possible solutions as well as future research aspects of NVIS technology will be discussed.

1.1. Background and Motivation

Among various medium frequencies in the range of 300 kHz to 3 MHz, and 3 MHz to 30 MHz radio applications [1], NVIS [3] technology has shown a significant importance for communicating in military as well as in emergency situations. Long-range military applications use typically frequencies in the ranges between 2 MHz to 12 MHz [4]. Three different propagation mechanisms can be defined in the frequency range of 2 MHz to 30 MHz. LOS propagation exists when there is direct visibility between stations. In ground wave propagation, radio waves follow the surface of Earth. Skywave propagation involves reflecting the signals back from the ionosphere. In this mode, medium and HF exhibits unique and special qualities. In fact, skywave propagation allows over-the-horizon communications, supporting connectivity between stations located even at opposite sides of the earth.

Emergencies strike in the blink of an eye. A successful information and communication technology (ICT) response in natural emergencies require immediate decision and response. A proper utilization of disasters relief procedures, local resources, and deployment the necessary equipment in challenging environments is advantageous. Due to poor communication technology resources, the risk of being unable to deliver vital assistance to the most affected communities is high. The information proves vital in the first few days of an emergency [8]. There are large number of examples where, highly reliable and redundant telecommunications system have failed during large-scale natural disasters. Some recent examples include Indian Ocean earthquake and tsunami in 2004, Kashmir region earthquake, India and Pakistan in 2005, the flooding of New Orleans after hurricane Katrina in 2005, Haiti earthquake in 2010, the Japan Tohoku earthquake, tsunami, and nuclear disaster in 2011, and tropical cyclone Haiyan in Philippines in 2013 [8], [9].

NVIS technology has gained recognition for its role of providing connectivity during emergency situations in large natural disasters. In situations of war or large natural calamities, the mobile phone, landlines, internet service, as well is electricity lines could be totally down [10], and providing connectivity could be a truly challenge. Due to telecommunication system break down, required disasters relief action could be impossible, medical help can no longer be provided, and comprehensive status information from the affected area cannot be gathered. So, there is an obvious need of communication to aid disaster relief programmes or making military tactics. When proper frequency selections and suitable antennas are designed, a successful NVIS communication is possible. The NVIS signal is directed towards and reflected from the ionosphere [11].

There are areas where telecommunication infrastructure still does not exist. There are areas where some infrastructure is present with irregular functioning. The easy propagation mechanism of NVIS technology enables radio communication in large area (about 200 Km radius) without the need of a network infrastructure [1]. Also, military communication systems always acquire independence of local infrastructure, which could be fulfilled with the NVIS radio propagation concept [1].

In the past, the cost of HF radio system was high. Modern cellular and satellite based communication provides higher throughput and hence, good quality of service (QoS) as compared to HF communication. However, there are emergency scenarios where system goes down, defence applications with security requirements, as well as there are underdeveloped regions around the world where it is very difficult to establish a cost-effective communication solutions. HF communication system hold a possible solution for the above mentioned problems. In addition to this, today technological development provides affordable HF system. Therefore, it is important to have an update on the research being done in this field [12].

As an example of a NVIS usage scenario, a simplified standard operating procedures flowchart to be followed during the emergency response to a natural disaster is shown in Figure 1. This procedure shows a recommended chronological action to be taken after a sudden humanitarian emergency. Initial assessment is done based on the emergency level and the experienced personnel deployed in the affected areas. Information sharing portion is crucial during natural disaster situation, without which relief aid is not efficient [8].

When considering the scope of this thesis work, one of the main considerations with NVIS technology is coverage which is normally in the skip zone, that is, areas which are too far away to receive groundwave signals. NVIS requires no infrastructure such as satellites or repeaters, two stations utilizing NVIS techniques can setup reliable communication without the assistance of any mediator. Furthermore, low areas and valleys are not obstacles for NVIS propagation, short and direct path to and from the ionosphere results in lower path losses. With reduced noise and interference, an improved signal to noise ratio (SNR) is achieved.

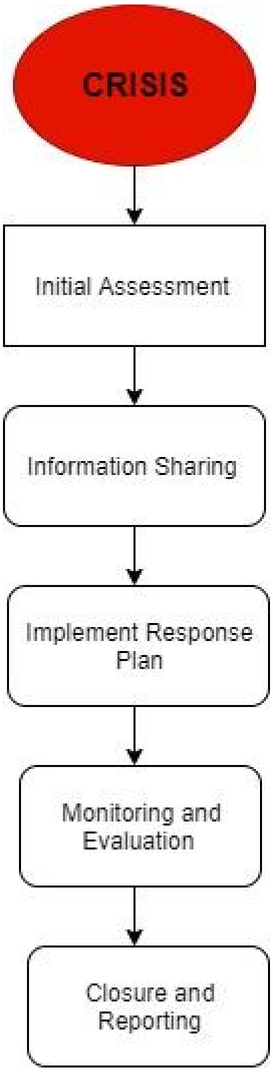

Figure 1. Simplified standard operating procedures during natural disaster.

NVIS transmission has been used for radio communication for a long time. However, the amount of scientific knowledge on NVIS antennas and on the mechanism for propagating NVIS is still limited. NVIS application may be of life-saving significance for emergency communications. The radio link is likely to display asymmetry in complexity when focus is in disaster relief. The field stations are likely to be small, lightweight, with portable antennas and battery-operated. Radio stations, which play a central role in communication, are likely to be located where electrical power is available, and will have more means to maximize their output power, which is important to compensate for the more improvised field stations. What is more critical is the awareness of the propagation channel and the appropriate equipment adaptation to it. Consequently, many prospects remain to develop NVIS radio communication systems through scientific study, e.g., in the field of antenna optimization, fading reduction, enhancement of channel capacities, and transmitter and receiver design.

1.2. Goal of Thesis Work

The main goal of this thesis work is to analyze the feasibility of using NVIS technology in various modern applications. NVIS is a popular technique for providing non-line of sight (NLOS) coverage in areas which lacks sophisticated infrastructure such as urban areas or remote access. This thesis work is mainly focused on investigating the key features of NVIS along with possible application areas. The knowledge of HF communication concept along with ionospheric wave propagation are essential to understand and develop NVIS application. The NVIS concept requires the presence of substantial ionization in the ionosphere directly overhead the transmitter, so some concerns about the effectiveness of NVIS operation during ionospheric changes needs to be discussed. Based on literature, NVIS propagation mechanisms is discussed along with that selection of frequency, NVIS antenna, and channel characteristics. Further, NVIS challenges, possible solutions, and future research aspects will be discussed. Since this thesis work is literature based, the initial work is more focused on the HF communication and ionospheric propagation concepts. Later, NVIS communications based on a system, propagation and an application approach are presented. Finally, challenges with possible solutions along with future possibilities will be topic of concern.

1.3. Contribution of Thesis

This thesis provides a comprehensive overview on HF development and its usage, ionospheric wave propagation, and NVIS technology. Particularly, the focus is on the NVIS communication concept, system model, future research aspects, as well as challenges and possibilities of NVIS communication in the future. Based on literature review and state-of-the-art related to NVIS communication system, this thesis explains the fundamentals of HF communication, ionosphere and its role in wave propagation, and NVIS communication – an important application of HF communication system. Moreover, some application field covered by NVIS in the past has been highlighted. All the parameters of a complete NVIS system will be discussed such as operational frequency and its variation based on season. Also, some antenna and their operation when implementing NVIS communications are discussed. Most importantly, NVIS challenges, possible solutions and future research aspects will be discussed.

1.4. Thesis Outline

This thesis is structured as follows. In Chapter 2, development and usage of HF communication are presented along with the ionospheric propagation concept. Details on the physical characteristics of the ionosphere that impact the propagation of the electromagnetic signal from the communication point of view are discussed.

Ionosphere and its behavior, different regions of ionosphere as well as ionospheric disturbances are presented in detail. Further, wave propagation in ionosphere, reflectional oblique incidences, ray paths, as well as a true and virtual path of a ray from transmitter to receiver via ionosphere are presented. Furthermore, the dependence of ionosphere on the operational frequency as well as ground-ionosphere-ground propagation are discussed.

Chapter 3 provides a literature review of NVIS technology. NVIS technology historic perspective, importance, its development in different time frames and features associated, and the application area are presented. In addition, the description of NVIS chains, propagation, antenna, and reception, as well as NVIS operation based on polarization and coverage are presented. Furthermore, a NVIS communication system for transmitting information from transmitter and receiver is presented in depth along with NVIS transmitter and receiver.

In Chapter 4, some challenges associated with the NVIS concept and possible solutions are presented. Further possible roadmaps of NVIS are discussed in this chapter. Finally, in Chapter 5, discussion and conclusions on thesis work along with some ideas on NVIS technology to make it more sustainable in future are presented.

2. BACKGROUND AND LITERATURE REVIEW

A typical communication system, can be divided into three portions: a transmitter, channel, and a receiver [13], as shown in Figure 2. The signal from the information source is passed through a source encoder, which converts the signal into a suitable form to be transmitted. To maximize the utilization of the resources, the processing unit removes redundant information from the baseband signal, then the encryption of signal is done so that the signal is secured and protected from any unauthorized access. Channel encoding techniques are applied to detect transmission errors and eventually correct some of these errors so that overall transmission quality is improved with reduced bit errors. Then, the signal is modulated by applying a desired modulation technique so that the signal can be suitably transmitted through the radio channel using an antenna. Some modulation techniques for this purpose are e.g. phase shift keying (PSK), frequency shift keying (FSK), and quadrature phase shift keying (QPSK). In case of multi-user communications, the modulated signal is multiplexed utilizing multiplexing techniques to share the valuable bandwidth. Time division multiplexing (TDM) and frequency division multiplexing (FDM) are two multiplexing techniques. The channel is the medium to transfer information from transmitter to receiver. The medium could be wired or wireless. A wireless channel is unpredictable, highly variable, and complex in nature. A channel may be subject to interference, noise, distortion, scattering, etc. The receiver function is to process the received signal and convert it back into the source information. Signals from the channel is received by a receiver antenna. Further, de-multiplexer action separates the desired signal from other multi-user signals. Furthermore, individual signals are demodulated using appropriate demodulation technique, aiming to recover the original message signal. A channel decoder removes the redundant bits from the messages. Since the message is encrypted, decryption of the signal removes the security and turns it into simple sequence of bits. Finally, signal passes through decoder which translate bits of information into readable original message signal.

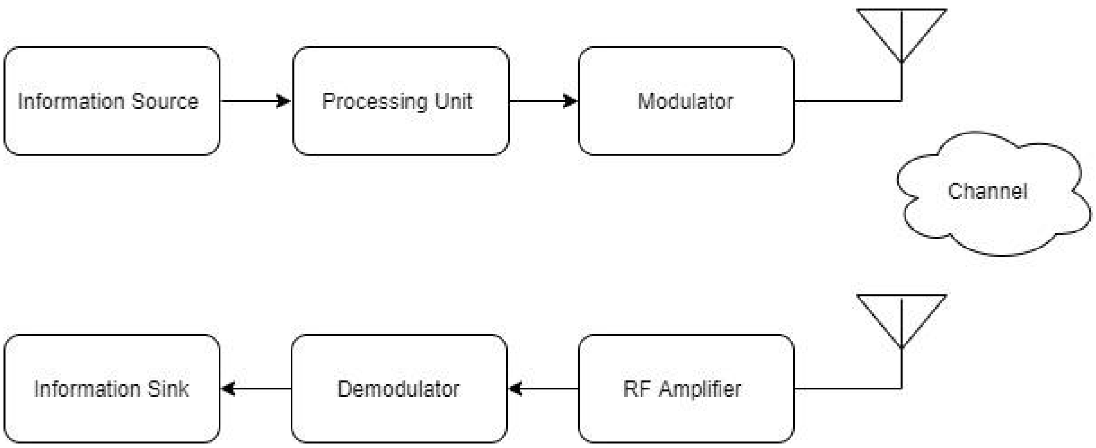

Figure 2. General communication system.

This chapter focuses on the theoretical background related to the NVIS technology. The literature review first covers the HF communications in general, its background and development are discussed. Further, ionosphere as well as propagation of signals will be described. Then, ionospheric propagation as well as various properties are discussed in detail. The use of ionosphere for the communication is presented with the mathematics behind it. A brief comparison between signal passing through ground, ionosphere and space is also discussed. Furthermore, some application from HF communication is also highlighted in this chapter.

2.1. High Frequency (HF) communication

On December 12, 1901, a young scientist named Guglielmo Marconi along with couple of his colleagues set up an experiment to test radio waves transmission over longer distance. Along with a number of strange looking instruments and a headphone fixed to his ears, he tried to receive a signal from a base station established in England. For a period, nothing happened and suddenly, Marconi lifted his hand, tuned in for a second, and a short time later gave the headphones to his associates for them to hear the snaps of the Morse letter S. It was nothing but the first successful event where Marconi was able to receive the telegraphic signal wirelessly. The snaps of the Morse letter S were sent from Poldhu on the Cornish coast and it was received at the dormitory at the Newfoundland, North Atlantic. The distance between the source and the receiver was 3000 Km mostly over the Atlantic Ocean. The signal was received by a wire antenna, kept upward by a high-flying kite, which had the height of 120 meters. This feat started a new era of communication and various long-distance wireless communication had been developed and is still going on, see [4], [14] and [15] for details.

The success of Marconi was soon known around the world and was the wellspring of discussion in scientific and engineering circles. However, one significant question arises- how did the radio signal discover the way back to the exact place where Marconi was sitting with his instruments on his hand and expecting the signal to arrive? Afterwards, other prolific researchers James Clerk Maxwell and Heinrich Rudolf Hertz found that the radio signals travel in a hasty manner and could be redirected from their path just in case they were confronted to something having electrical properties unique from those of the ether [4]. In 1902, Arthur Kennelly in America and Oliver Heaviside in England independently discovered the presence of the conducting layer in the upper region of the Earth's atmosphere, and they indicated that the deflection of the radio waves may be caused by this layer of Earth's atmosphere. However, the researchers were not able to understand how this layer would influence the propagation of the radio waves. Meanwhile, the researchers were busy conducting further analysis and experiments [4]. It was quite a long time before some could prove the hypothesis given by Kennelly and Heaviside in 1902. The first direct verification on the conducting 'Kennelly-Heaviside layer' or E-region was provided by Appleton and Barnett, almost twenty years after the hypothesis was given. Moreover, the height of the reflecting region was also estimated see [3] and [16] for further information. This layer is named as 'Ionosphere' because these layers were made of the electrically charged particles called ions. These experimental results did not provide the existence of the Ionosphere but also unveiled some other properties such as height. In 1926, Breit and Tuve revealed that a wave bundle or a small duration pulse sent out from a transmitter generates two or more impulses instead of one in a receiver place a few kilometres from the transmitter. The behaviour corroborated the existence of the ionosphere further. Of the two impulses received at the transmitter, the first is due to the direct wave travelling along the ground while the second is the indirect wave reflected from the ionosphere, as shown in Figure 3. In 1950, the institute of the radio engineers (IRE) characterized the ionosphere as a part of the external atmosphere where particles and electrons are available in amount adequate to influence the propagation of radio waves [17].

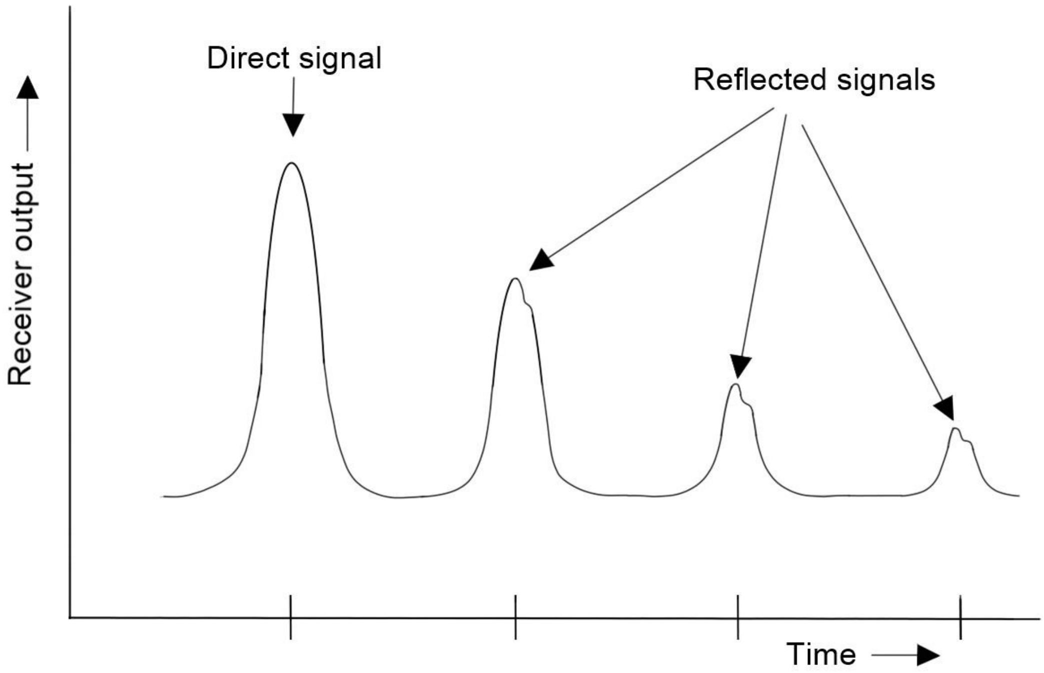

Figure 3. Receiver response to a HF signal.

The possible results of the long-distance communication as well as the rapid fluctuations in the intensity of the radio signals, and the clear direction on the propagation of waves due to radio signal fading were further elaborated by Appleton. The ionosphere's E region is considered in order to lie somewhere in the range of 90 and 150 Km above the ground. Moreover, in another trial [16], he examined the difference in time delay between the groundwave and the skywave for the pulse transmitted over a 5 Km range. These tests were performed to confirm the hypothesis on radio wave propagation in the ionosphere. From that case, vertical sounding has been used comprehensively for investigation into properties of the ionosphere, with growing precision and refinement. Medium frequency transmissions have a relatively short viable range during the day, and even at the night, when their range was increased considerably, their signal strengths diminish at a lot greater rate than that of long wave carriers. Subsequently, it was accepted that the longer the wavelength better the propagation [4], [15], [16], [18]. Generally, HF radio waves are one of the fundamental means for long distance communication because of low costs of terminal hardware, adequate transmission capacity, agreeable signal quality, and low power requirements [14].

2.2. HF Development and Usage

The HF radio range (2-30 MHz) usage spreads over a wide scope of business and military applications. Spectrum occupancy and the user's interest for channel assignment are of key importance. As an overall communication, the HF frequencies is subjected to the global radio guidelines, which have been created by the International Telecommunication Union (ITU) in Geneva. These guidelines incorporate radio range usage and assignments inside the HF band. Assignments are made dependent on the service type or use. Some of service types are [4]

- Point-to-point communication between fixed HF circuits.
- Radio communication between mobile HF circuits.
- Radio communication based on specified frequency band for scientific research purposes.
- Aeronautical mobile radio communication between a land station and an aircraft or between the aircrafts.
- Broadcasting radio communication expected for direct reception by the public.
- Radio communication carried on by people keen on the radio procedure exclusively with an individual point and without financial interest.
- Coastal radio station communication.

An HF radio framework has a unique feature of providing LOS communication without utilizing radio relay techniques. HF radio works at the carrier frequencies that conceivably propagate to any point in the world through at least one reflection from the ionosphere. In any case, such "skywave" links are subjected to complex interactions between the solar and terrestrial environments, and the ability to communicate straightforwardly between the arbitrary sets of points by means of HF may not be a reliable approach under all conditions. Regardless of the vulnerability of the connectivity, the ability to communicate over thousands of kilometres without the requirement for costly infrastructures has made HF radio an important and popular innovation since the early 20th century, and the innovation is being developed continuously to propel the unwavering quality of HF radio communication [19].

HF is utilized generally to meet public and the strategic communication requirements. Telecommunication companies and privately owned businesses are the main clients of the fixed services. HF provides a method for communication to remote places where any alternative services are technically or economically challenging to provide. Numerous small-scale organizations use HF to sidestep the expense of the long-distance phone charges of the carrier networks. In the starting phase of the development of remote mining and exploration, HF radio signals were used, well before the ordinary telephone service were available exploiting microwave relays or land lines. Additionally, HF service is deployed among international embassies and missions in a several nations. The radio facility is generally situated in the embassy building itself with the receiving antennas placed on the rooftop. In underdeveloped nations, HF usage is relatively common as a primary source of the communication because the satellite communication infrastructures are not as good as in developed countries. The United Kingdom (UK) Foreign and Commonwealth Office controls the communication network between the Foreign Office in London and every British embassy in the world. Albeit a considerable amount of the communication is performed by phone, telex or public network over satellite or cable, about 60 embassies are connected to the UK Foreign and Commonwealth Office by a HF radio telecommunication network in the past. Furthermore, in the past, commercial aircrafts as well as shipping used the HF radio waves for communication with the base station. Aeronautical mobile services are usually acquired by commercial airlines. In coastal regions, usually the ground wave mode of propagation is used for long-distance communication while ships in the sea use the skywaves to communicate with the bases in shores, as the skywave approach seems to be much effective and cost efficient. Military also use HF generally for both vital and strategic communication, either as a primary form of communication or as a backup. Military forces use the skywave for most of their communication, but some armed forces use the ground wave transmission too. Since the satellite communication is considered an expensive mode of communication, the substantial amount of communication relies on the HF for use in land, ocean, and air tasks. The UHF is effective only when the transmitter and the receivers operate in LOS. The main reliable methods for communication must utilize surface waves or short-range sky waves. Such communication is accomplished by utilization of the low frequency end of the HF band [4].

Innovation of the HF technology during the late 1970s has been noteworthy. Advanced HF equipment combines the high-level automation and microprocessor control to reduce the human intervention and to reduce the workload on the operators. There have been significant advancements in automatic tuning and antenna matching systems, remotely controlled systems, solid-state circuits and synthesised frequency selection systems. Moreover, highly stable oscillators, frequency agile synthesisers, fast tuning antenna couplers and solid-state power amplifiers offering the possibility to improve the quality of the HF communication considerably, could be very expensive. In addition, Very Large-Scale Integration (VLSI) has had an astonishing effect, which is already evident in all types of communication systems. This helps in reducing the size of the equipment, increasing the energy efficiency and the overall system's reliability without compromising the system performance. It also helps to integrate the new and complex features in the existing systems, which have not been previously possible due to the lack of the necessary systems. The marriage of the HF communication systems with computer technology offers an effective approach to improve the performance and quality of the communications. The emphasis has been on utilizing the latest technologies to tackle the traditional shortcoming of the HF communication systems. Specifically, the choice of a suitable channel has been complete automated by various systems and further increased utilizing robust data modulation and coding schemes, which can cope with the challenging effects of the radio channel. Simultaneously, hardware development has reduced the size and the cost of the radio equipment whilst significantly expanding its capacity and performance [4].

2.3. Wave Propagation

HF communication through ionospheric reflection has multiple application especially in military, aeronautical, oceanic and emergency service communications with remote locations because of economic and management reasons and as reinforcement framework. The capacity, availability, and usable frequencies of the channel are determined based on the state of ionosphere in order to establish long distance communication [17]. Radio waves that propagate from a transmitter to a receiver close to the surface of the Earth can take one of a few potential ways. The long and far-reaching utilization of HF radio for a regular citizen, government, and military communication can exploit several valuable methodologies for utilizing HF radio. A communication channel is the link between the transmitter and the receiver. Figure 4 shows the propagation of the radio waves as a ground wave, skywave and space wave. A wave that travels over the surface of the Earth is called the ground wave. The electromagnetic waves emitted from the transmitting antenna propagate along the surface of the Earth, which is a ground wave. The propagation range of the ground waves is limited, and it may not extend much past the horizon. An extended LOS range is few hundred kilometers over ocean, less over land. Ground wave propagation does not experience the ill effects of a skip zone yet is restricted by landscape or man-made obstructions. In skywave propagation, the electromagnetic waves produced from the antenna are received after being reflected from the ionosphere. This beyond LOS approach permits communication range over thousands of kilometers however it needs the utilization of frequency that will propagate under the instantaneous ionospheric and the terrestrial circumstances. At the typical frequency range where the signal is reflected from the ionosphere, the communications with the nearby base (node) may not be possible because of a steep take off angle. When the transmitter sends a signal with a steep angle, the signal penetrates past the ionosphere rather than reflecting on Earth. This range of excluded areas is called skip zone. A space wave incorporates the immediate, ground reflected, ridge diffracted, tropospheric refracted, tropospheric scattered and ducted modes. In satellite communication, the up-link earth station sends the signal to the satellite and the satellite change the frequency of the signal and amplify the signal before sending it back to the Earth, which is received by the receiver on the ground. Due to the shape of the Earth and the imperfect conducting layer, the propagation theory of the ground waves incorporates many mathematically important issues. The wave which originate as approximately spherical shape from the source can be viewed as the plane wave by the time it enters the ionosphere because of the high curvature. The ionospheric layers bend as a result of the Earth's curvature, yet in many issues this curvature is neglected [19], [20], [21].

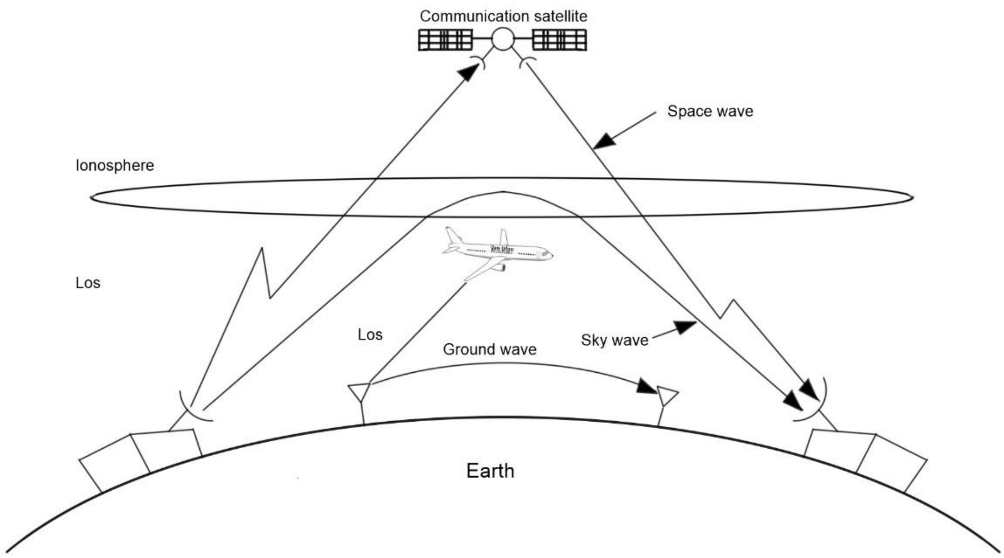

Figure 4. Radio wave propagation through ground, ionosphere, and space.

One of the main advantages of using the HF radio communications is the economic one. The relatively inexpensive aerial systems can be installed since the actual location of the transmitter is not critical and the commercially manufactured receivers can be obtained at reasonable cost. Moreover, in HF communications, the static interference issue is not as serious compared with the medium frequency bands. One of the primary hindrances of ionospheric communication is that because of variations in the ionospheric condition it is important to determine the usable frequency range for successful communication. The changes in ionospheric condition from hour to hour, day to day, month to month, and year to year may demand long-term and short-term changes in frequency. This is a clear drawback, as more than one channel may have to be assigned to a station and it is not a practical solution for users to change the setting of their receivers through different parts of day or year [22]. To propel the dependability of HF radio communication, development of novel techniques has been persistently created over the years. Advanced signal processing has been implemented to handle the fading and Inter-Symbol Interference (ISI) associated with HF channels to increase the data rates on narrowband channels. Medium access protocols have been created for sharing the scarce spectrum. The link management protocol development has automated the job of finding usable frequencies, with relaying concepts that make reliable worldwide coverage possible. The data link protocols for channels as well as modem characteristic shows potential to create versatile HF links under changing channel conditions to keep up the maximum achievable data throughput [19].

2.4. Ionosphere

The ionosphere is the ionized part of the Earth's atmosphere that plays a vital part in the propagation of the radio waves. It is accepted that ionosphere influences radio waves predominantly because of the free electrons. The movement of an electron in the ionosphere is affected by the magnetic field of the Earth and the interactions with the other particles. The impact of the Earth's magnetic field is to make the ionosphere a doubly refracting medium. Electrons are distributed roughly in horizontally separated layers, so that the density of the electrons is a function of the height of the layer above the surface of the Earth. The ionosphere is electrically neutral until there is a presence of some charged particles that give rise to electrical forces that would prevent the formation of stable layers. In addition to the electrons, heavy negative ions can also be formed by the attachment of electrons to the air molecules [4] [20]. The reflection of the HF waves back to the Earth from the ionospheric layer depends on the number of free electrons per unit volume in the ionosphere, the height of the ionized layer, operating frequency, incidence angle and so forth.

As shown in Figure 5, the ionosphere comprises of electrically charged particles and atoms. The ionosphere lies in range 60-1000 Km above the Earth's surface and plays a significant role in the wave propagation. Ions are produced in the Earth's atmosphere partly due to the cosmic rays and mostly by the solar radiation. The historical development of the ionospheric research has divided the ionosphere into many layers based on the height from the surface of the Earth. Ionosphere is the part of the atmosphere where the free ions exist in enough amounts to influence radio propagation [14]. Free ions dispersion can be characterized as regions that are organized in roughly horizontally classified layers. Some ionospheric regions have identical composition and are ionized by specific wavelengths in solar radiations. The ionosphere is composed up of two principal layers known as E and F. The E-layer has a maximum electron thickness at a height of around 110 Km. Different radio estimations have been utilized to estimate its height, the penetration frequency and their variation with the time of day and season. The electron density just above the maximum of the E layer is not easy to estimate but it is likely that it is somewhat less than the maximum value for the range of height spreading right up to the base of the F-layer [20]. The D layer alongside two significant ionospheric areas E and F inside the mesosphere and thermosphere are shown in Figure 5. The charge particles in ionosphere are influenced by the magnetic field of both Earth and Sun, which results in Auroras. Auroras as caused when high energy particles form the sun interact with the atoms in the ionospheric layer of Earth’s atmosphere. Auroras as mainly seen around the Earth’s magnetic poles, which are bright and a beautiful band of lights [1], [23]. The F-layer peaks at the height of 175 Km from the surface of the Earth, the oxygen absorbs the extreme ultraviolet (UV) radiations. In the E-layer, which ranges from the height of 60-150 Km above the ground, the oxygen absorbs the soft X-rays and UV radiations. The D-layers which is below the E-layer, and at the height of 60-90 Km, acts primarily as an absorber, causing signal attenuation in the HF range. It mainly contains free electrons that recombine with oxygen ion during night, creating uncharged oxygen molecules. The D-layer, responsible for the high attenuation of lower frequencies during the daytime, completely disappears at the night. By daylight, the F-layer is partitioned into F1-layer and a higher F2-layer [1], [4], [14], [17].

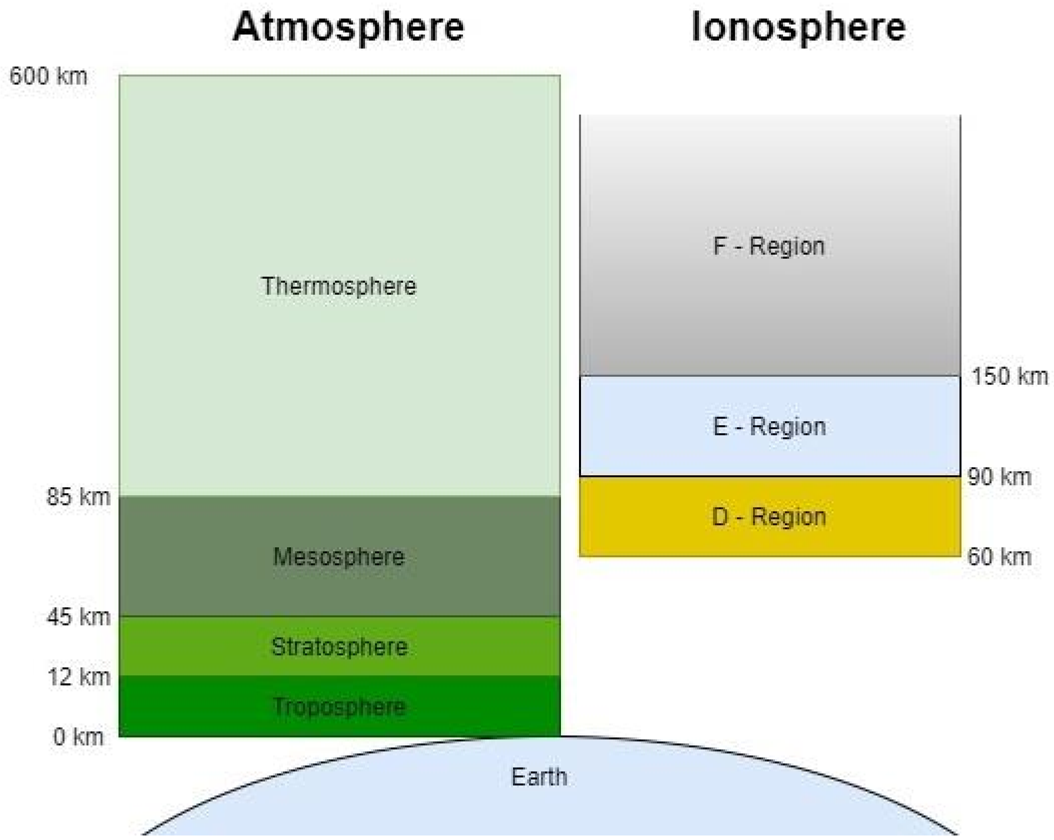

Figure 5. The ionospheric regions.

The primary source of ionization in the ionosphere is the electromagnetic radiation from the sun extending over the ultraviolet and X-ray range of the spectrum. Various rates of the ionization at different altitudes depend mainly on the intensity of the solar radiation as a function of the wavelength and the ionization efficiency of the neutral atmospheric gases. The variation in the ion density at different altitude depends on many factors such as an atmospheric path, solar zenith angle, diurnal and seasonal variations and the position of the sun. UV radiation causes the most ionization in the ionosphere. The ionization uses electrons or certain amount of the energy at each moment thus reducing the radiation intensity. As a result of this, the UV radiations induce bulk of ionization in the upper region of the ionosphere. At lower elevations, extreme UV radiation and X-rays give rise to most of the ionization [4], [17].

The electron density in the D-region displays huge diurnal variations. The electron density is minimum at the night-time and maximum shortly after the local solar noon. As the density of the electron increases in the atmosphere, electron collision frequency also increases. Hence, the energy absorption of the propagating radio waves takes place in this region. This region is investigated using very low frequency (VLF) waves so that the wavelength is so long that the interpretation of the observations is much less direct that at high frequencies [4], [20]. The height of greatest electron layer thickness is around 110 Km in E-region, with practically 10^{11} electrons/cubic meter. During night-time, only a small residual part of the ionization stays in the E-region. The solar cycle dependence exhibits a maximum layer density at solar sunspot maximum.

The F-region is mainly divided into two subregions, F1 and F2 layer. The F-region extends upwards from around 130 Km. F1 sub layer starts from 130 Km and ranges up to 210 Km altitude, which is also called the occasional reflecting layer for HF transmission. However, most of the time, the incident waves that penetrate the E-region also penetrate the F1-layer and are usually reflected by the F2-layer. The F2-layer, which ranges form 250-400 Km above the surface of the Earth, is usually used for long-distance communication. Since the F2 layer is very high above the ground, it is strongly influenced by diffusion, winds, and other dynamic effects. Hence, a sophisticated model is required to represent the F2 layer. Usually in the night-time, the F1 layer disappears and the absorption capacity of the E- layer also diminishes, which result in the night-time field intensities and noise to be generally higher than daylight [4], [20].

Any changes in the ionospheric properties may cause an interruption of the communication. The primary reason for the interruptions is reduction of the F2 layer electron densities, or enhanced D region absorption. Hence, it is critical to examine physical reasons for ionospheric disturbances. Sudden ionospheric disturbances (SID) causes because of unusual high ionization densities in the D region. This is a result of abrupt upheaval in the sun. This phenomenon brings about unexpected increment in the absorption of the medium frequency (MF), HF, and VHF radio waves. Disturbances can happen all through the polar area in high geomagnetic latitudes, which are called polar cap absorption (PCA). PCA are caused primarily by high-energy solar protons which are guided by Earth's magnetic field towards the polar region. Another sort of disturbance can be ionospheric storms, which are brought about by the floods of charged particles of solar origin diverted by the Earth's magnetic field towards the auroral zones [4].

2.4.1. Use of Ionosphere for Communications

Significant amount of research has focused on the ionosphere because it acts as a time and frequency dispersive channel in the HF range. The strategy for the portrayal of the ionospheric performance as a communication channel is mostly driven by the means of the ionosonde, which is a transmitter that covers the whole HF frequency range with an antenna playing out a similar efficiency in all the frequency range with vertical arrangement [17]. As shown in Figure 6, refraction happens when the electron concentration changes. In Figure 6, four different media with different refractive indexes are considered. The radio wave travelling through the ionosphere confers a swaying movement to electrons [24]. Along these lines, re-radiation happens which changes the speed of propagation of the wave and the refracted waves returns to the Earth if the frequency is not too high. If the Earth's magnetic field were absent, the oscillating electrons would be parallel to the direction of the electric field of the incident wave. Hence, re-radiated waves would have the same polarization as the incident wave and would propagate through ionosphere without the change of polarization. The Earth's magnetic field modifies the oscillatory motion of the electrons that leads to them to move in complex orbits. The layer is partitioned into various thin strips with constant electron density and each strip has a higher electron density than the one below. This variation in the electron density would cause a ray to bend, as shown in Figure 6. Snell's law at the boundary of each stripes explains [20]

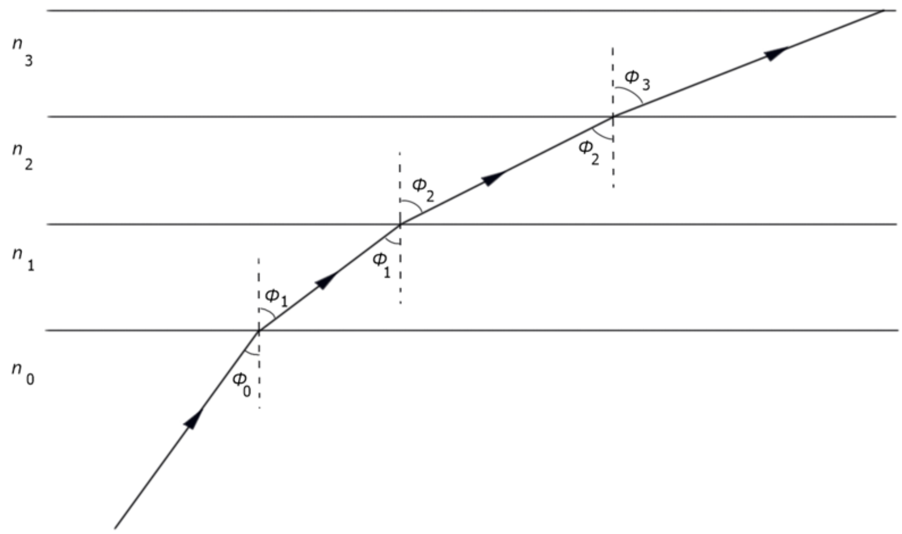

Figure 6. Refraction in layered medium.

$$n_0 sin\Phi_0 = n_1 sin\Phi_1 = \cdots = n_n sin\Phi_n. \quad (1)$$

Thus, a ray entering the ionosphere at an angle of incidence Φ_0 will be reflected at a height where the ionisation is such that *n* has the value

$$n = sin\Phi_0. \quad (2)$$

If the effects of the Earth's magnetic field are ignored, then the ionosphere refractive index n is given by [14]

$$n^2 = 1 - \left(\frac{f_N}{f}\right)^2, \tag{3}$$

where f is the wave frequency and f_N is the plasma frequency which is proportional to square root of the electron concentration.

Since the refractive index of the vacuum is 1, a wave impinging upon the ionosphere enters a zone where the refractive list gradually diminishes as the concentration of electrons increases with height. If the ionized layer is thick enough, the refraction will continue until the angle of refraction reaches 90 degrees. In reality, the electron concentration variance is constant, and the beam path is like the continuous curve [4], [14].

At vertical incidence, the state of reflection arises when n is equal to zero and from (3), this occurs where $f = f_N$. If $f = f_v$, represents the vertically incident frequency reflected at the point where the plasma frequency is f_N then for the obliquely occurring wave

$$sin^2\theta_0 = 1 - \left(\frac{f_N}{f}\right)^2 = 1 - \left(\frac{f_V}{f}\right)^2, \tag{4}$$

And therefore

$$f = f_v sec\theta \, . \tag{5}$$

Thus, a frequency f incident at an angle θ_0 on the ionosphere will be reflected from the same electron density (height) as the corresponding vertical incidence frequency. Hence a given ionospheric layer will always reflect higher frequencies at an oblique incidence than at a vertical.

One of the particular attributes of HF radio skywave propagation is a strong dependence of the path loss with the operating frequency. For all intents and purposes, the most noteworthy frequency on a given point-to-point link is controlled by existing ionization of the area of the ionosphere where the propagating wave is refracted. The frequencies that are well above the critical value are not bent adequately to return to the Earth. The measure of the bending free electron density required for the bending from the ionosphere to the Earth depends on the angle of arrival from Earth. This angle is at maximum for NVIS operations [25]. In Figure 7, we can see the beam paths as a function of the elevation angle for a fixed operating frequency leaving the transmitter. For the low elevation angle, the path travelled by the beam is long and hence the range, which is represented by the ray 1 in Figure 7. As the elevation angle increases, the path travelled by the ray decreases until the skip distance is reached. However, for higher angle of elevation the range is still large, see for example ray 4 and 5 in Figure 7. A critical angle is reached when the electron density in the ionosphere is not enough to reflect the ray back on the Earth. The rays that are emitted at the angle greater than the critical angle escape the ionosphere and such rays are called the escape rays. The high angle rays that have a range as long as the rays with low elevation angle, usually occur between the skip ray and the escape ray and hence are dispersed over the great range. Signal strength of these rays is weak however they carry considerable amount of information. The critical angle is function of the frequency. For a given ionization distribution, the frequency at which the critical angle reaches zero is called the critical frequency. This is the maximum frequency which can be reflected at vertical incidence and for the frequencies less than or equal to the critical frequency there is no skip distance.

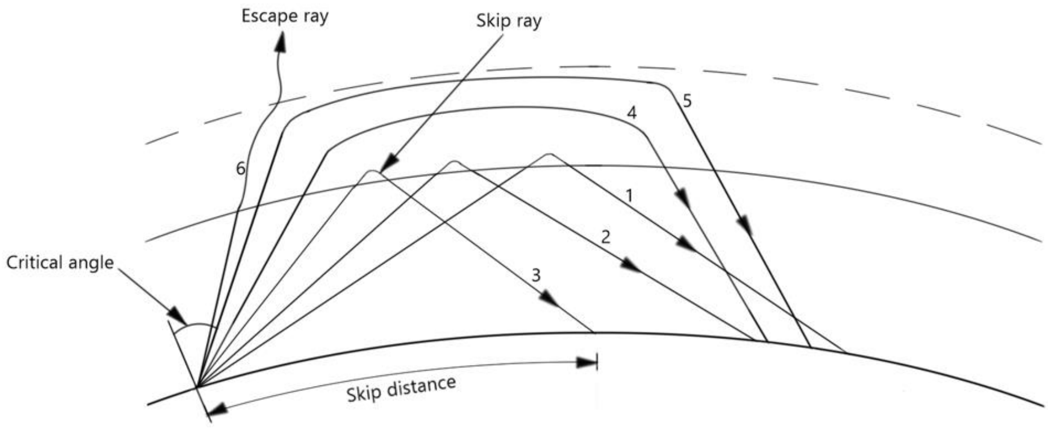

Figure 7. Ionospheric radio wave propagation.

The ionospheric properties are investigated by calculating the essential frequencies at various layers. The most well-known technique is where a short pulse is radiated from the transmitter vertically upwards. A receiver receives both direct and the signal reflect from the ionosphere and calculate the time delay. The virtual height is then determined from this time delay between the direct and the reflected signal. This height is essentially the height from which the wave tends to reflect if the ionosphere is replaced by the perfectly reflecting surface at such a point that the wave velocity is equal to the velocity of light. As we know that the wave speed in the vacuum is always greater than the speed at the ionosphere, hence the virtual height of this layer is higher than the actual height, as shown in Figure 8. The virtual length between the transmitter and the receiver is given by the angle TAR and true length is given by angle TBR [4], [12].

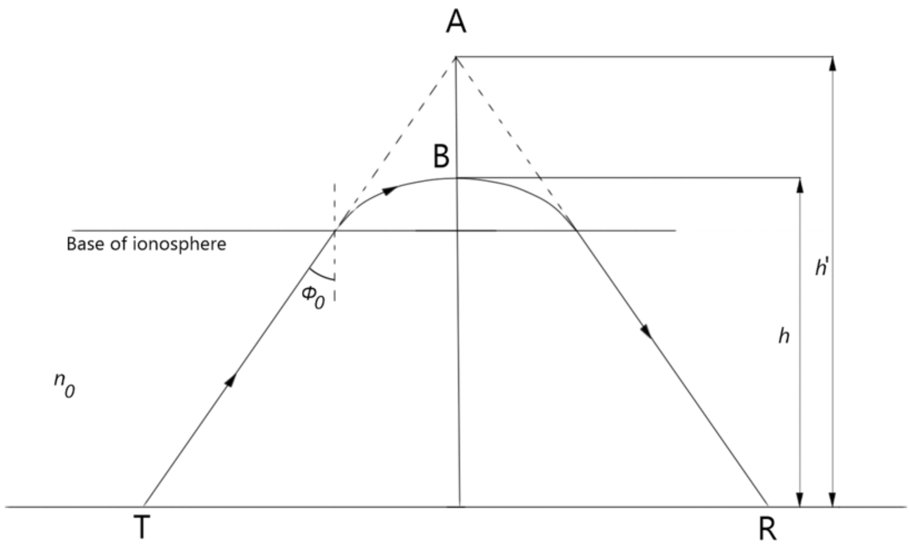

Figure 8. True and virtual path.

Ground wave communication is more natural than skywave communication, so the ground wave can be considered to be simply a weakened, delayed, however in any case undistorted variant of the signal. Although the skywave suffers from much greater variability in attenuation and delay, it also suffers from fading, Doppler frequency shifting and spreading, time dispersion and delay distortion.

The dispersion created in the mediums unit impulse response can be depicted as multipath attributes. One or more of following can cause time dispersion

- high and low edge skywave
- skywave returns including distinctive number of jumps
- groundwave and skywave paths
- skywave gets back from various ionospheric paths
- splitting of the magneto-ionic components resulting from the effect of the Earth's magnetic field.

Every propagation way or mode has its own group delay characteristics. The dispersion of the medium is brought about by the delay between the various modes in bunch delays, which can result in inter-symbol interference when the signal rate is comparable with the relative multipath delays. Hence, the successful sequential information transmission rate is limited to the reciprocal multipath propagation time range. It is itself a function of frequency, path length, geographic location, local time, occasional movement, and sunspot. Operating in reference to the maximum usable frequency (MUF) will optimize the information rate [4].

During high-speed HF data transmission, multipath propagation has a significant impact on the given communication methodology and support equipment. Because of inter-symbol interference, the channel output is reduced, and high error rate can result even at high SNR. Operating at frequency well below the MUF increases the risk of facing large multipath delays. The skywave signal oscillate with some characteristic amplitude and phase and the signal received by the static receiver is steady no matter how irregular is the ionosphere. Thus, the fading rate can be attributed to ionospheric changes. Three different fading can be characterized by their roots and the main cause of this fading are the movement and the curvature change of the ionospheric reflector, the rotation of the received polarization ellipse axes and time variation and absorption and change in the density of the electrons. Other than these impacts which can be generated independently for every mode, more serious fading can result from interference between two or more modes, especially when they are roughly equivalent in amplitude [4].

In HF skywave communication, the transmission loss depends on various factors which affect various aspects of a communication link. The variation of the electron density on a day-to-day basis on the E and F-layer of the ionosphere affects the direction of the ray path that takes to reach the receiver through the ionosphere. This variation in the direction of the ray path can alter the effective gain of the receiving and transmitting antennas. Different focusing effects, spatial attenuation, transient losses, losses of polarization, and the multipath propagation are common effects of the change in the directions of the ray path. The change in the electron density at the D and E-region of the ionosphere influences the ionospheric assimilation considerably. These can cause a day-to-day fluctuation in the noise intensities. The daily variation of the signal strength is analysed across wide variety of the tracks and operating conditions. The largest variation occurs on the path that range between the 65° to 70° geomagnetic latitude [4].

The availability of the skywave is known as the probabilistic rate of the radio signal able to propagate over a given skywave path at any given time. The concentration of the electrons distributed along the path of the propagation determines the upper limiting frequency of the propagation of the skywave. This upper limit is commonly known as the MUF and it can be viewed as the wave's maximum frequency that can spread over a given skywave path. Since the ionosphere's properties go through transient changes, the MUF varies constantly; but the forecasts of ionospheric conditions depend upon monthly median conditions, and some arrangement must be made for day-to-day fluctuation. Subsequently, the anticipated MUF is characterized as the frequency for which, inside a given period, signals are relied upon to be accessible at a given hour for 50 % of days [4].

2.4.2. Ionospheric Propagation Prediction

The ionospheric variability information is required for the proper selection of the optimum frequency, the required transmitter power, antenna configuration, etc. Variability prediction can be classified into two approaches. First, the network operator needs a short-term frequency prediction in order to predict the MUF failure rate and increase the circuit's reliability. Secondly, a long-term frequency prediction is needed for arranging the terminal installations. This requires both a network designer and a frequency allocator personnel. The three most significant parameters to consider are the range of the usable frequencies, the power necessity of the circuit and the information on the elevation angle for the antenna design. The long-term variation of the ionospheric parameters is tied closely to the sunspot cycle, albeit no totally acceptable measure of the solar activity is available (a 12-month running average sunspot number is generally utilized) [14].

These ionospheric regions are called the layers. Each layer has its own attributes and the letters (D, E and F) are generally used to indicate these layers starting from the ground upwards. Radio wave reflection against the E-and F-layers is liable for most propagation of ionospheric radio waves. The D-layer which is only present during the daytime or the daylight hours induce an attenuation which is inversely proportional to the frequency of the operation [1], [26]. Prediction of the critical frequencies depends on diurnal, seasonal and the topographical variation or the sunspot number. The behaviour of the E and F1 layers helps in predicting the critical frequencies in terms of the zenith angle and the sunspot number. The behaviour of the F3 layer is very complex and hence cannot be represented analytically, so an acceptable practice to take the monthly median value of the critical frequency. The radiation angle depends on the height of the reflection of the waves. Thus, it is widely accepted that it is more precise to determine the elevation angle if the height of the reflection is known [14]. ionospheric propagation results in various losses of the signal between the transmitter and the receiver. The loss that occurs in the ground in the ground wave mainly depends on the conductivity of the ground and on the angle of elevation of the incident radiation. The sea surface is a good conducting surface, so the loss is less, while the loss is relatively higher in the desert. Ionospheric absorption depends on several parameters such as a sunspot number, solar zenith angle, season, operating frequency and the radiation angle.

Knowledge of the diurnal variation of optimum working frequency (85% of MUF) helps the network operator in foreseeing network failure because of penetration of ionosphere by the signal. For some random transmission separation, the MUF is determined from the product of the critical frequency and the MUF factor which is a function of the transmission distance. This distance is related with a certain angle of the elevation of the transmitter waves. At MUF, the ray path is that of the skip ray, as shown in Figure 7. For this situation, the wavelength of propagation is hence the minimal (skip) distance at which the ionospheric wave hits the Earth. For a distance of about 2000 Km, which is the limit reached from the E layer in a single reflection, the MUF may be determined by choosing the maximum between E, F1 or F2. The MUF is not a sharp limit and hence for frequencies higher than the classical MUF, propagation is always possible however the average operating frequency may be considerably greater than the MUF. This happens because both the atmosphere and ionosphere are not ideal reflecting surfaces. This irregularity causes the scattering of the signal and leads to propagation beyond the wave limit. Ionospheric tilts can also play a role in increasing the operating frequency to raise above the MUF. For a given transmitter output power, as the operating frequency decreases, the intensity of the signal received also decreases due to the absorptions by the ionosphere. As a result, noise power increases which lead to the deterioration of the SNR and eventually circuit reliability. The Lowest Useable Frequency (LUF) is the minimum frequency below which the reliability is unacceptable. The LUF depends on the transmitter power, the noise level and the factors that determine the path loss. Other mechanisms such as scatter processes, polarisation changes caused by the Earth's magnetic field, the spatial spreading of the energy, and focusing and defocusing caused by the ionospheric curvature limit the energy of transmitted signals [4], [14].

Within the ionosphere, the electrons are set in motion by the radio waves and the Earth's magnetic field exerts a bending effect on the paths of the electrons. At the point when an incident radio waves impact the ionosphere, it split up into ordinary and the extraordinary components because of the effect of the magnetic field. These modes are differently affected by the magnetic field. The extraordinary wave is recognizable from the ordinary just in the upper areas of the layer F. The path and velocity of the propagation of both ordinary and the extra ordinary is different due to the different refractive index. Subsequently, these waves are reflected at various heights arriving at any receivers with various delays. The ionosphere is a dynamic medium in terms of propagation, especially if working with low and high latitude. In this sense, for the communication system to work intensively in the ionospheric environment several preliminary processes should be conducted, and a set of metrics should be investigated depending on the frequency of transmission, the latitude and the time of the day [17].

The ionospheric sounding method provides constant real time updates on the radio propagation conditions over a radio connection using essential framework comprising synchronized transmitter and the receiver. Along these lines, from this method, the time delay between the transmission and the receiving can be used to identify the effective ionospheric layer altitude [17]. A few designs and methodologies have been proposed by the authors in [14], [27] to acquire the key parameters of the ionospheric channel, such as

- frequency and temporal dispersion by mean of the scattering function
- signal to noise ratio
- link power attenuation
- time of flight
- phase stability
- angle of arrival
- independent measurements for ordinary and extraordinary rays.

Calculating the performance of an HF skywave link is a complex and challenging task but there is much that can be learned from analysing the dependencies of some relevant characteristics, of which critical frequency is particularly important. The critical frequencies of the ionosphere's E and F2 layers are the highest frequencies which can be reflected from two regions; they are associated with the maximum electron densities in those regions. As the electron concentration in F2 region is dense compared with E region, the critical frequency value of F2 region is greater, so critical frequency in F2 region is of major concern. Unfortunately, F2 layer does not follow a simple solar zenith angle law, either diurnally or seasonally compared to E and F1 region because of variation [14].

2.4.3. Ground-Ionosphere-Ground Communication

During the propagation on the ground, the ground wave radiates energy along the Earth’s surface until it arrives at the point where the energy level turns out to be too low for the communication. Figure 9 shows the radio wave propagation of the HF signals (2-30 MHz) [1] as the ground and the skywave. A ground wave provides robust communication for short-range communication and control functions. The ground wave is diffracted over the Earth’s bulge between the transmitter and the receiver and refracted in the lower Earth atmosphere. The reliability ground wave link is mainly determined by the signal frequency, antenna patterns and the propagation environment. For the prediction of desired HF system range performance during receiver signal level measurement, a proper identification of dominant propagation mode is significant [21]. The attenuation of the ground wave propagation is mainly due to the nature of the geographical territory it is being propagated and the obstacles encountered. As seen in Figure 9, during skywave propagation, the transmitter sends the signal on the ionized surface above the Earth [28] and this surface reflects the waves back on Earth to be received by the receiver. The maximum radio intensity will be received by the receiver if the path difference between the ground wave and the skywave is a whole number of wavelengths. However, if the path difference is odd or half wavelengths, the minimum radio signal intensity will be experienced because of destructive interference [2], [16], [18].

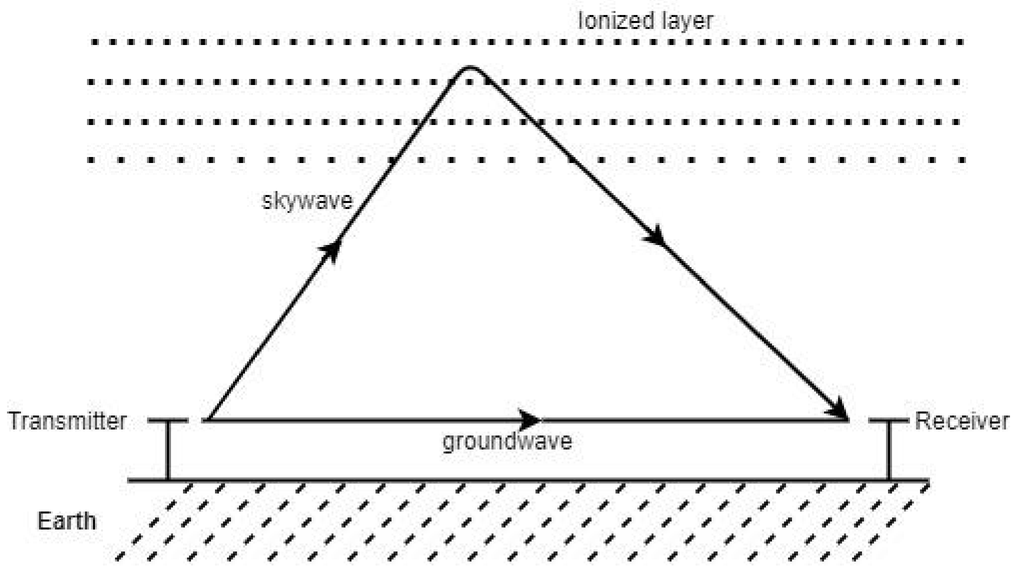

Figure 9. Propagation of radio waves.

The HF waves that are propagated through the ionosphere are mainly used for the distant point-to-point communication and information broadcasting. There has been a consistent study regarding the nature of the link due to the ionospheric propagation. High gain rhombic or log periodic antennas are used mostly for point-to-point land fixed HF propagation. Also, arrays of horizontal dipoles with considerable directivity are popular for the broadcasting using the skywave mode. Since a transmitter with high transmitting power are readily available, the strength of the skywave links can be enhanced even more by good engineering design and practice, namely equipment and antenna systems. HF communication to mobile devices possess significant problems. During the mobile communication, the receiver may move around a fluctuating terrain, ranging from few to thousands of kilometres, which means the different modes of propagation size. This imposes a physical limitation on the antenna which may degrade its efficiency and the radiation patterns obtained may not be suitable for propagation. The limitation on the primary transmitter power may cause serious acoustic and electrical noise on the mobile end of the terminal. In case of an aircraft, the height may give rise to a further multipath propagation mechanism, however, the speed may cause the Doppler shift. Hence, to achieve satisfactory outcomes over an HF connection of this sort, caution must be given to the terminal radio gear, the development of an operation link and the administration of the frequencies to be utilized over those connections. Knowledge of the general framework factors is basic to the satisfactory design and execution of HF portable radio connections [1], [3], [12].

Although the ionosphere is crucial for the HF communication, some problem like ionospheric variability, absorption, polarization and the radio noise still affect the communication that occurs through ionosphere. The median curves on the ionospheric variability measured over a long period typically shows a smooth characteristic that veils any momentary fluctuation. The median measurements show a smooth long-haul correlation with the smoothed sunspot number (SSN) which is a convenient solar index. On the other hand, the short-term correlation is poor because of the chaotic behaviour of the solar flux. The absorption of the radio waves takes place due to the collision with the electrons, neutral particles and the ionized particles. Generally, the absorption of the wave in the ionosphere is divided into two kinds, deviate and the non-deviate. Non-deviate ionospheric absorption can usually be seen during the daytime ionograms, whereas the deviate absorption occurs when the operating frequency at the vertical incidence is close to the critical frequency. Wave polarization depends on the geomagnetic latitudes and angles of incidence [24]. A wave entering the ionosphere can be classified into two separate waves with distinct characteristic. Polarization that happens at the bottom of the ionosphere also called the limiting region is called the limiting polarization because the descending wave no longer varies with the height once it passes below. The orientation for the circular polarization is described as left-hand or the right-hand polarization [20]. The general rule for understanding the sense of rotation is described by the authors in [14]. When the thumb points in the direction of the magnetic field B_o, the rotation of the extraordinary wave vector is given by the fingers of the right hand and the rotation of the ordinary wave is given by the fingers of the left hand. The external noise due to the various sources such as atmosphere, galactic and human generated noise affect the sensitivity of the HF receiver. Due to the simultaneous presence of the multiple strong signals, HF receivers do not usually have low noise figure but instead require good signal handling capabilities. Usually, the noise level decreases as the operating frequency increases. The existing optimum working frequency (FOT) guidelines encourages the operation on lower frequencies where the noise level may be higher. The trade-off between the higher and lower frequency must be maintained because the operations on the higher frequencies may yield improved SNR but the path loss is lower in the lower frequency operations, which will offset the increased noise to some extent [29].

3. NEAR VERTICAL INCIDENCE SKYWAVE

Cutting-edge global communication has progressed enormously due to the technically innovative regional, national and international communication networks. Modern society is so dependent on the telecommunication systems that it has a devastating effect if the communication system goes down due to natural disasters or others. It is obvious that in emergency situations, the communication link between the disaster-hits area cannot convey critical information to authorities, and without knowledge of the current situations in such areas, sending help may not be effective. These situations call for highly reliable communication infrastructures, backed by redundant networks. During crisis caused by natural disasters, it is quite common that the telecommunication infrastructures are damaged [30] which may cause lack of coordination between the helping parties, electric power infrastructures to be down and damaged or blocked roads [31]. One possible choice of communication during this critical time is HF NVIS, which has provided compelling effectiveness. Also satellite communication can be a viable alternative [8], [11]. Satellite communication provides a higher bandwidth compared with HF communication. However, satellite communication is not always a reliable solution. We can take the example of the New Orleans flood in 2005. The authorities were unable to establish satellite communication with the concerning parties due to various problems ranging from expired subscription and non-programmed gear to the antenna pointing problems, caller overload [14] and also due to the high satellite bandwidth consumed by the news video, satellite telephones did not function at all [3].

NVIS is the one of the distinct cases of skywave operation, where a HF signal transmitted almost vertically to the ionosphere is reflected back and received by a transmitter with a close vertical angle. Since transmission angle is almost vertical, the NVIS process needs a considerable presence of ionization in the atmosphere, otherwise the signals may penetrate the ionosphere, not returning to the ground station. As the ionization is dependent on the solar radiation, so effectiveness of the NVIS operation may be limited during absence of the solar activity [25]. The main feature of the ionosphere is that it is a natural reflector, and it forms a natural passive repeater or reflector provided by the sun [28].

The network should be as simple and as effective for communication with the disaster-hit areas. A highly effective and reliable communication channel is necessary for coordinating the relief efforts. The choice of the communication system and the related propagation mechanism however depend on the size and the topology of the disaster hit areas. For instance, if the area is small, LOS communication can be easily established using the UHF/VHF repeaters. Whereas, if the disaster hit area is large, it will be almost impossible to install a communication infrastructure. In this case, NVIS wave propagation offers an outstanding alternative. The NVIS propagation permits HF communication over distances, typically ranging from 400-500 Km, utilizing frequencies typically in the range of 2-10 MHz. Thus, NVIS is particularly suited for the disaster relief communication where the disaster spread over a large area. Since NVIS communication does not require local communication infrastructures, it is also used for communication in remote areas in the developing countries where the telecommunication infrastructures are not well developed, for military applications etc. NVIS propagation can have a single transmitter covering a large territory. However, the receiving signal may typically suffer from various time and frequency distortions due to the multipath effects. Since the NVIS operation is dependent on the solar activity on the ionosphere, the NVIS communication channel varies because of the varying solar activity along the day, year and multiple year cycles [32], [33].

Although there is an increasing amount of scientific and engineering development in the NVIS communication field, many areas such as NVIS propagation mechanisms, antenna, and transceiver design still need to be further developed. The primary objective of this thesis work is to study the possibility of NVIS telecommunication systems for disaster relief communication in terms of improved link reliability. This goal is pursued by literature review and analysis of key articles on NVIS telecommunication systems.

3.1. Radio Communication via NVIS: An Overview

The main advantage of using the NVIS framework is that it does not require network infrastructure, satellite or repeater to provide communications in large areas. Various types of radio communication have been developed for reliable information transmission in these scenarios and the research community is still enhancing these systems. Radio waves in HF could be diffracted due to obstacles such as hills, building etc. leading to the diminishing of the signal strength. Moreover, during the ground wave transmission, other various factors can affect the signal strength like folliage, ground conductivity etc., hence this approach cannot provide a reliable service for long-range communication. NVIS, in the above-mentioned case can provide reliable service when LOS is blocked. As shown in Figure 10, the NVIS waves projected towards the ionosphere, and reflected back to the Earth by the ionospheric layers. As seen in Figure 10, it creates an umbrella type coverage, which covers a large area on Earth's surface. By choosing a suitable frequency in the HF band, it is possible to achieve vertically directional aerial patterns that provide relatively efficient broadcasting assistance up to 320 Km radius without producing undue interference at distances greater than this. In the World War II, NVIS systems were used for ground-to-ground communication by armed forces when transmission problems were faced with VHF equipment operating in jungle and mountainous areas [1], [4], [22].

HF radio skywave propagation (including NVIS) has an anomalous behaviour in which the path loss depends on the operating frequency. The ionospheric layer where the propagating wave is refracted defines the highest frequency on a given point-to-point path. The frequencies above the critical frequency do not bent adequately to return to the Earth, and hence they cannot be used for communication purposes. The bending of the wave depends on the free electron density and it increases with the angle of arrival of signal. This angle is at its maximum for the NVIS operations [25].

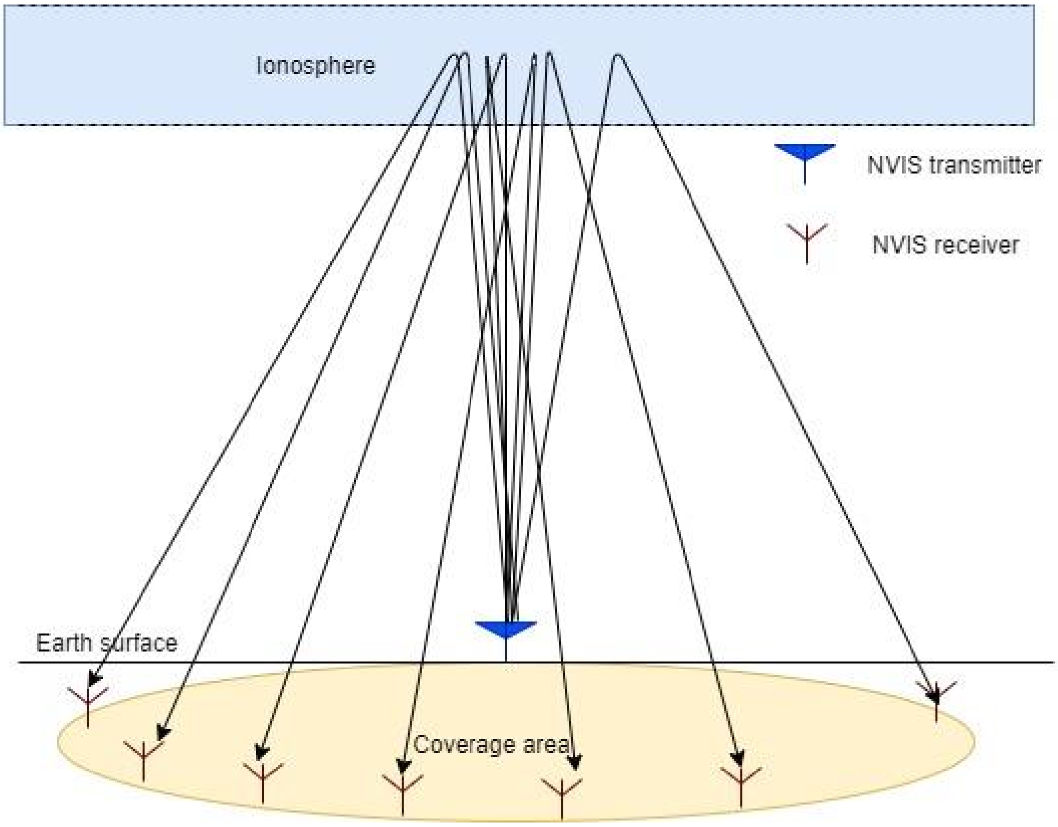

Figure 10. Radio wave propagation via ionosphere (simplex).

Authors in [11] highlight the significance of the HF wireless communication during crisis. During the Hurricane Hugo emergency in Puerto Rico, the shared resource concept program organized by federal agencies for interoperability of radio message between points to points was of major concern. A network of 22 stations from 10 federal agencies were-linked and an urgent request message on the medical supplies need were acknowledged. In addition to providing resources, success in coping with emergencies is critically dependent on human planning from the provision of plans and procedures to the successful use of people and equipment. Notwithstanding giving assets, accomplishment in adapting to crises is subject to human planning from the provisions of plans and methodology to the effective utilization of individuals and equipment. In ionospheric reflections-based communication, the waves are transmitted at high angle so that the ground-based obstacles have little to no effect on the signal strength [27]. However, the path finding on the reflected waves that are coming from high angle is more difficult as the bearing errors increases significantly with the reduced transmitter range. The ionospheric propagation technique utilizes waves transmitted at high angles from the ground such that territory obstacles such as mountains or hills have little or no effect on signal strength [27]. The propagation of NVIS is primarily single hop through the ionosphere's F2 region, so it is necessary to choose the correct operating frequency for successful NVIS communication. In addition, the designed antenna system aims to maximize radiation at high angle of elevation [29].

3.1.1. NVIS Communication System

Any functional system is the collection of different parts assembled in a way that they portray unique properties, which the parts in isolation do not. The radio system is also a collection of different individual systems, which consist of a transmitter, radio channel, and a receiver. The transmitting subsystem converts the input, which may be some kind of information, to radio signals as output. The radio channel then takes the output from the transmitter as the input and passes the signal across the propagation medium and delivers it is to the receiver input terminal. The receiving subsystems then takes the transmitted signal, convert it to the information, and delivers the signal to the required destination. To perform all operations, power is the need, so battery power is utilized in case of emergencies or at the places where the power source is not available. Optimizing the whole NVIS communication framework will altogether reduce the power budget needed for the connection. Research on antenna parameters, propagation mechanism, diversity, channel parameters modulation techniques and coding are needed for system optimization [3], [11], [12]. A single input single output (SISO) NVIS system is shown in Figure 11.

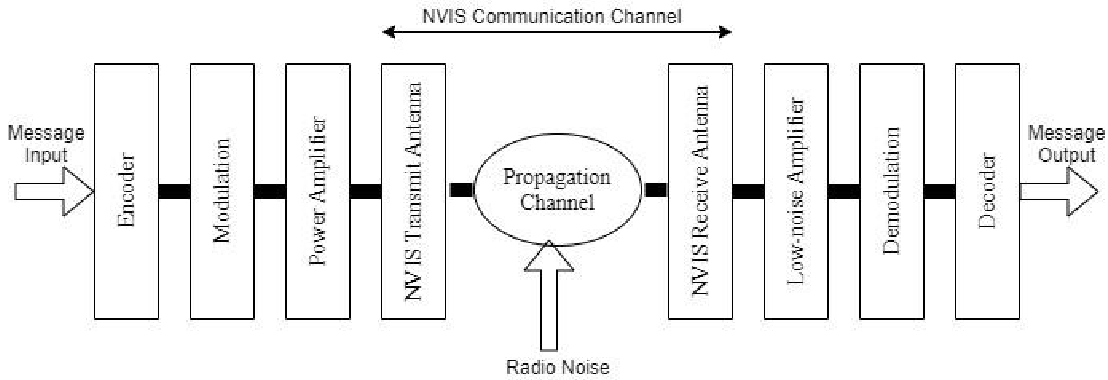

Figure 11. NVIS communication system.

A regular crisis typically takes place in just a single territory or area. In this manner, the best frequency determined by propagation characteristics is chosen. The key requirement is to provide a communication path between two stations. The NVIS antenna is typically only a couple of feet off the ground. A fixed station NVIS receiving antenna is horizontally installed. As high angle radiation is required for NVIS operation, a horizontal polarized dipole antenna is preferred. However, a dipole antenna in a vertical ‘vee’ configuration can meet the radiation requirement for NVIS application. A NVIS antenna is omnidirectional in nature which implies that the energy radiated from the antenna is of equal strength in all directions from the antenna. All radio stations which lie in the range of antenna will receive the signal which are equal in strength and without the gap in the coverage or ‘skip zone’. A NIVS antenna must be low and no more than 20 feet above the ground. A multi-frequency NVIS antenna requires a remote and automatic antenna tune at the end of the coaxial cable and before the antenna system. For a NVIS system, the typical working frequency is between 2 MHz and 5 MHz during the night-time and during the daytime it ranges from 5 MHz to 10 MHz. However, these frequency ranges as well as dispersive characteristics of the ionosphere depend on frequency, angle of incidence, time of a day, the Earth’s magnetic field, season, and solar activity [14].

3.1.2. NVIS applications

Ionosphere knowledge is of practical significance since radio transmission between various locations around the globe rely on this knowledge. The ionosphere output determines the dispersive time frequency characteristics of the channel, the SNR, and the radio link availability. The availability of the channel affects the likelihood that a connection can meet the minimum SNR, achieving a certain level of service. Natural disasters can impose power supply or installation time limitations in order to deploy complex infrastructure. For this reason, HF NVIS technology makes emergency communications a highly attractive application. The key advantages offered by NVIS are the simple assembly of the infrastructure since the requirements are met by a single dipole, the low power requirements for establishing a communication connection, and the NLOS needed to cover broad distances [17].

One important question may arise namely, why to use a NVIS system when already the VHF/UHF and repeaters exist? It is apparent from the operating principle of NVIS that what it achieves can be also obtained by other systems operating in higher frequencies. VHF and repeaters can ensure the communication that NVIS supports. A well-developed repeater framework is productive in operation; however, they are not effective in catastrophic situations. In such case, the NVIS come into play, providing solutions during the time of catastrophe. The ionosphere may serve to port radio signals starting with one terminal then onto the next now and again when repeating equipment cannot, and when territory forbids direct VHF/UHF contact [5].

Considering today's densely interconnected world, in the model of internet of things (IoT), where various types of machines are interconnected with each other, a network that is capable of communicating with the equipment that are situated hundreds of kilometre without any external infrastructure is certainly very attractive. If we think about terrestrial communication in past two decades, peoples and things in marine are less connected as people or things in space. In this kind of scenario, remote IoT is a possible solution. One good example company that is pioneer at providing HF based solution is KNL networks, Oulu, Finland. Authors in [11], [30], [31], and [34] expand knowledge of disaster impact on the telecommunications power infrastructure. In the abovementioned articles, the authors present the findings from both on-site surveys conducted during real catastrophe such as Hurricane Katrina in October 2005 and various reports from industries and government agencies. In time of disaster, the communication infrastructure is mostly damaged, or the energy supplies are interrupted, and roads are blocked. Since today's society is so connected, the complete loss of communication following a major disaster has a devastating impact on the society and may lead to another disaster. During such difficult times, NVIS communication have proved to be an excellent alternative for first responders in several natural disasters, for example, the 2004 Indian Ocean tsunami and the 2005 Hurricane Katrina flood in New Orleans. NVIS communication is also an attractive technique for military purposes. Since all the signals returning to the Earth have the same strength, direction finding on the signal becomes very difficult result in reduced likelihood of intercept and detection. Moreover, the signals during the NVIS communication are radiated vertically, which helps in concealing the equipment to prevent from being noticed while maintaining the excellent communication channel. Furthermore, the NVIS antenna is much flatter and therefore harder to detect [1].

Authors in [35] and [36] recommend NVIS communication techniques that can provide low-cost communication to remote and poor areas. There has been substantial progress in connecting the undeveloped or developing countries. In areas where the telecommunication network is not available due to financial problems, NVIS communication may be a possible solution for the telemedicine and tele-education, voice and data transmission. In [21], the applicability of the NVIS systems in deserts is considered, where the groundwave communication can be limited to the radio line of sight. Several radio propagation tests regarding the groundwave in both urban and rural desert environment show that the limited groundwave propagation is due to the low surface conductivity. This issue can be eliminated using NVIS modes for most short-range HF communications.

The concept of automatic link establishment (ALE) for HF radio propagation mechanisms (including NVIS) for the operating frequency as well as antenna is presented in [19]. One of the highlights of HF radio skywave propagation (including NVIS) is a substantial reliance of path loss on operating frequency. A typical technique for characterizing and utilizing the best frequencies is called ALE. Generally, an ALE network radiates energy on each pool of assigned frequencies, and different nodes ascertain and record the productivity of the arriving signal from each station at each frequency. This database would then be utilized to pick a frequency to use with each other node.

3.2. NVIS propagation

The operating frequency is the main factor determining if the electromagnetic waves entering the ionosphere will be refracted back to Earth. In Figure 12, the skywaves are radiated towards the ionosphere at an upward angle from the antenna and reflected to Earth's surface through the ionosphere. Typically, the range of the reflected wave is no less than 160 Km from the antenna. The skip zone is covered by the ground wave propagation. In the skip zone, no signal can be received from the transmitter operating at certain frequency. If the skip zone appears undesirably, then mostly it is due to human error. The error may be the improper selection of the antenna or the antenna height. Hence, the skip zones can be eliminated by adjusting the antenna heights and the transmitter frequencies that produce the high angle radiation. The skip zone can be easily handled by investigating the operating frequencies and the polarization of NVIS devices [1]. The wave impinging into the ionosphere penetrates the ionosphere and continues in space if the operating frequency is too high. The signal radiated with low frequency is reflected back to the Earth in every angle including the zenith. This results in energy hitting the Earth in an omni-directional pattern without skip zone if an efficient short-path antenna is used. Hence, the penetration of the signal outside the ionosphere can be prevented by lowering the frequency of the signal. Moreover, to obtain the NVIS operation, the signal must be radiated strongly enough from horizontal angles greater than 75 or 80 degrees and using frequencies at which the ionosphere reflects the signal. The ionosphere reflects the signals in an umbrella pattern without the skip zone. Due to this behavior of the NVIS operation, if any ground wave is present in the region of the NVIS operation then it may cause unnecessary interference of waves known as fading due to destructive interference from skywave and groundwave [1].

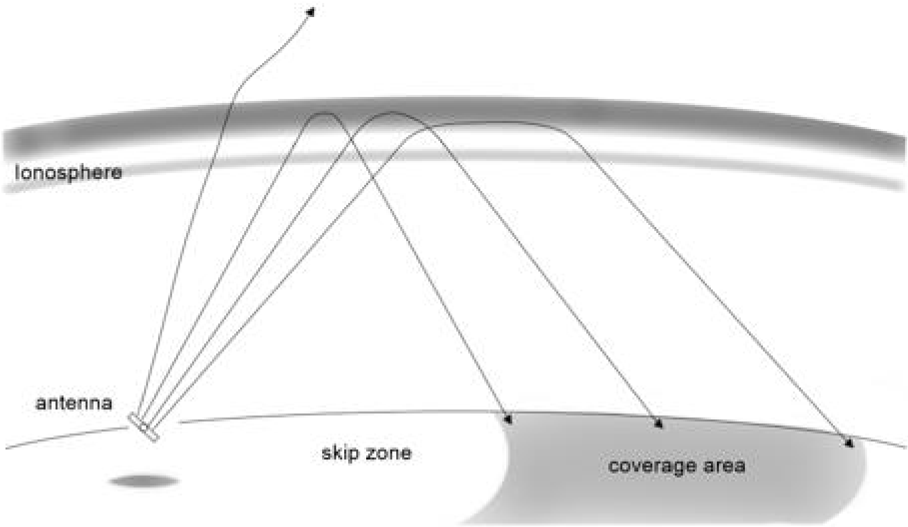

Figure 12. Transmission above critical frequency of the ionosphere results in a ‘skip zone’.

Radio communication mainly depends on the ionospheric signal reflection ability and at the same time also depends on other main factors such as the signal’s operating frequency, signal’s angle of incidence, etc. The signal’s angle of incidence is the angle between the perpendicular line to the ionosphere and the angle at which the signal is emitted to the ionosphere, as shown in Figure 13. The signal that is parallel to this perpendicular line or the signal is incident on the ionosphere vertically exhibit zero degrees of incidence angle. NVIS communication uses zero angle on incidence, that is, during the NVIS communication the signals are sent almost vertically upwards to the atmosphere to be reflected vertically downwards to the Earth. Proper planning of this communication system based on NVIS operation leads to a highly reliable, skip zone free communication in HF bands. In Figure 13, we can also see the launch elevation angle which is different from the angle of incidence. Generally, in NVIS operation, the signals are transmitted to the ionosphere with an angle of incidence less than 45 degrees due to which the reflected signals are close to the transmitter while maintaining the continuous coverage with the absence of skip zone [1].

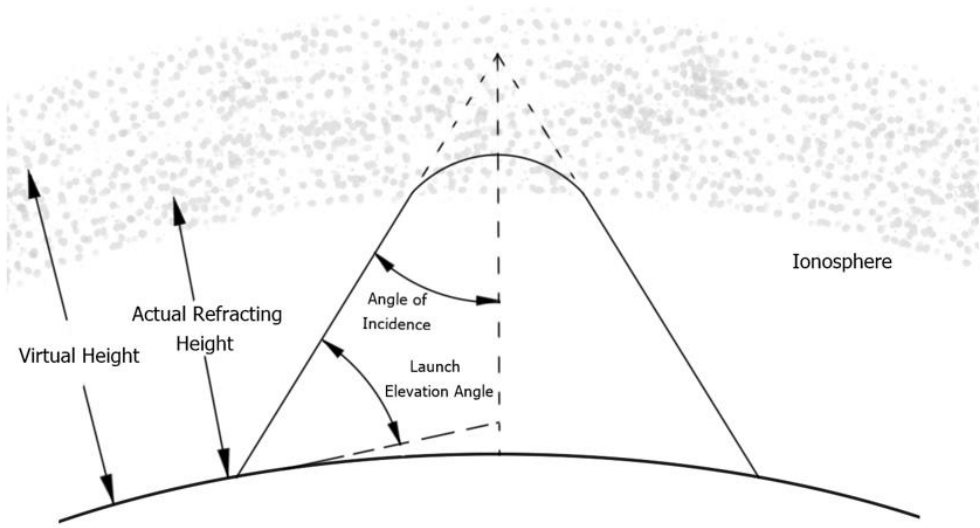

Figure 13. Ionospheric radio wave propagation.

The omnidirectional nature of the NVIS operation antenna allows to transmit the signals with equal strength in all directions. This omnidirectional behaviour can be clearly seen in Figure 13, where the signal is transmitted to the ionosphere in a near vertical direction at a frequency low enough so that they are reflected back to the Earth. The reflected signals form a circular coverage area and the receivers located in this circular region created by the reflected signals, receive the signal at approximately the same strength without skip zones. To attain this uniform signal strength, the antennas should focus the signals with angle greater than 45 degrees in elevation plane. This system setup may help in establishing links to remote areas within 300 to 400 Km range from the central station. NVIS communication technique can be implemented in Antarctica, where the communication infrastructure is not available [1].

3.2.1. Selecting Frequency

The selection of the frequency is an important factor to consider while choosing the NVIS communication. The frequency is typically different for the short-range skywave communication and the long-range applications. For the short-range communication, the best frequency operating range is between 2 to 10 MHz. The pass band position is determined depending on the daytime, season of the year, sunspot activity, geographic location etc. Polarization and directionality of the radio waves are additionally significant when utilizing the contact method of NVIS. It is easier to have a horizontally polarized antenna, with greater gain at radiation angles below the zenith. An antenna which provides a significant vertical component will improve the performance of the close-in signal by propagating the ground wave. Frequencies in the 10 MHz area may be used during periods of high daytime sunspot activity. Service during periods of low sunspot activity is limited to frequencies of 6 MHz and below. However, the MUF is generally less than 2 MHz for certain winter night conditions with low sunspot number. Depending on these factors, an admissible frequency range is set such that enough signal intensity is achieved. If the operation frequency is changed by even 1 MHz from the admissible frequency range, there would be significant loss in the signal strength or about 10 dB or may even result in the loss of the signal altogether [4]. The choice of the HF operational frequency usually results in better signal strength with lower noise rates but not necessarily lower interference rates.

In addition to LOS 'skip zone free' communication, it is now obvious that the use of the NVIS method provides certain barriers to its use that must be understood in order to mitigate them. The primary issue is the groundwave and NVIS interference. When both NVIS and the groundwave signal are present, disruptive interference can be triggered by the groundwave. For this reason, proper antenna selection will suppress and decrease groundwave radiation while optimizing the amount of energy that goes into the NVIS mode. Second, during the operation of the NVIS system, the high take-off angle issue should be taken care of. In order to produce near-vertical radiation, antennas must be carefully selected and positioned so that the energy radiated towards the zenith is optimized. The energy can be maximized by using specially built antennas or locating 1/4 to 1/10 wavelength standard dipole antennas from the ground to direct the energy towards the zenith. Third, frequency selection should be performed with caution. There is a critical frequency in NVIS propagation above which the ionosphere will not usually reflect radiated radiation but will pass through it. This frequency is roughly related to the incidence angle and to the highest frequency used. This means that in accordance with the path length, the useful frequency range varies, i.e., the shorter the path, the lower the MUF and the lower the frequency range. The LUF is mainly characterized by the efficient radiated power and the receiver's noise and interference. In fact, this restricts the operating mode of the NVIS to 2-4 MHz at night and about 4-8 MHz during the day. The variance of these limits is dependent on sunspot cycles that cannot be regulated by engineering. The frequency range between LUF and MUF is minimal, so assigning a frequency can be an issue. All the above-mentioned disadvantages of NVIS transmission, except for the limited frequency range, can be solved by engineering. If these problems have been addressed, many communication advantages are possible [1].

The Earth’s magnetic field exerts a force on the moving electrons within the ionosphere which are set in motion by the radio waves. This phenomenon split the wave into two components as ordinary and extraordinary waves. Both waves have different polarisations and they can be assumed to propagate independently throughout the ionosphere and are subject to different absorption levels. A minimum path attenuation should be considered by means of a transmitting antenna whose polarization helps to excite a powerful ordinary wave and a receptor antenna polarization matching the larger solved linear portion of the coming ordinary wave. With respect to the losses of polarization coupling, NVIS is not concerned with the antenna polarization. There is a much greater need to discriminate against the ground wave. The minimisation of vertical polarization will accomplish this. The advantage of horizontal polarization can also be noticeable in terms of interference discrimination. Polarization is also useful in filtering against noise in order to relay short range transmissions at lower frequencies. The use of vertical polarization insensitive antennas, when the most interference occurs through ionospheric, is possible to achieve very large increases in the signal-to-noise ratio during the day [4], [20].

3.2.2. NVIS Antenna

NVIS involves ways in which ionosphere reflects high-angle radio radiation. It provides simple and powerful cross-regional networking. With all due regard to the propagation conditions, it is important to select a proper operating frequency. In addition, it is necessary to use an antenna which has a large radiation area in the vertical direction. The NVIS antenna, perhaps the most important feature in the radio communication, consists of an inexpensive and efficient simple wire structure, if the designers have sufficient knowledge and such antennas are optimally mounted. Optimizing antenna radiation patterns for NVIS elevation angles guarantees major radio transmission channel enhancement. The loop antennas are ideally designed for mobile NVIS applications because they are compact enough to maximize instantaneous latency and efficiency at low frequencies. Transmission of NVIS is only possible at high elevation angles, optimizing the antenna radiation pattern at these elevation angles will improve efficiency of transmission and improve the signal-to-interference ratio at reception [1], [37], [38]. The selection of an antenna in tactical NVIS systems depends on the field conditions, the required range of operating frequencies, the antenna system components available, the reliability of the base station for which communication is to be formed, the available transmitter power, the time and energy of the system, the enemy's prospection of signals interception and specific mission requirements [1].

Practical NVIS wavelength are between 30 and 100 meters and require a larger antenna for NVIS. With fixed device installation, this form of antenna installation is feasible. Some examples of fixed mounting antennas are Delta Antenna [39], Log-Periodic Conical Spiral Antenna [40], and Vertical Rhombic Antenna [41]. Further, vertically directed Log-periodic dipole antenna (LPDA) [1] is famous for military applications. It is not suitable to use the above mentioned NVIS antennas for field expedient application as their transport is cumbersome and installation time consuming, even impossible in some terrain. The desired flexibility of the simple and light wire antenna for good NVIS performance can therefore be assured. In [42], a basic dipole wire antenna which may be suspended between trees or from an extensible lightweight base show a gain of around 6 dB at high angles.

The common understanding on NVIS is that both the transmission and the reception are done using a similar antenna which may not be the appropriate solution. When designing a NVIS receiver, the average directivity is important as compared to antenna gain, as electromagnetic ambient noise limits the transmission if the receiver's sensitivity is not very high. Effective judgment of the receive antenna radiation pattern between the NVIS elevation angles and angles at which most distortions and ambient noise arrives may significantly improve reception [43], [44]. A combination array composed up of several active elements and spatial filtering can improve the SNR as ambient noise is limited. A comprehensive study of propagation of ionospheric waves as well as radio wave propagation must be performed in order to configure the NVIS antenna [1], [3], [14].

The transmitting and reception properties of the used antennas must adhere to the intended propagation function and avoid unintended propagation. A vertical radiation pattern that supports high elevation angles for NVIS must be used while choosing the antenna. For mobile applications, small loop antennas are common. The larger string wire antennas between current or portable mast systems have improved antenna gain and more flexibility for ad-hoc field operations. Many identical antenna components may be placed into arrays to have an enhanced pattern of radiation [43]. The antenna arrays are large and need many supports, diverse networks and phase lines. In contrast, the receiving antennas consists of many small, low weight active antennas with much simplified low power splitters and phasing harness. Such an antenna set for base stations can be used easily in ad hoc operations. New HF radio transceivers, which allow the use of separate transmission and reception antennas, can be used for emergency base stations [1].

3.2.3. NVIS Channel Characteristics

To build a modulation and coding architecture that minimizes BER with maximum throughput for any ionospheric communication, a sounding device covering the entire HF band should be built [45]. Multipath fading induces fast and strong (down to -30 dB) fade in seconds. Awareness of the mean signal value is insufficient for the design of communication systems; fading affects receiving of data substantially. Fading rates are stated in terms of autocorrelation of the time series. Autocorrelation deals with the speed with which a point in time series is decoupled from its nearby point. This time difference measured by autocorrelation is usually called coherence time and it has direct affiliation with the Doppler spread of the channel. Channels with large Doppler spread have signal mechanisms that change in phase over time, and since the fading depends on whether the addition of components is constructive or destructive. The coherence time must be considered when choosing the symbol time of the modulation, to guarantee that the channel has an approximately constant response during the symbol. The time gap between the arrival of the earliest multipath component and the arrival of the latest multipath component is known as delay spread and it is a measure of the multipath of communication channel. A modulation should be planned, to obtain an ISI-free channel, to such a degree that the length of the symbol is long enough (normally 10 times the delay) [1], [46].

In the course of time, the standard ionospheric model for performance evaluation of HF communication systems evolved from Watterson model [47] to the Furman model [48], in which both long-haul and NVIS measurements are performed to model SNR variations to improve Watterson model. In addition, Hervas [49] developed techniques of polarization to boost system performance. Several references [14] and [20] on the propagation identify the physical processes of ionosphere. In the case of HF-communications, ionosphere studies can be divided into 3 regions, each having its own peculiarities: a high latitude polar zone, low altitude medium latitude and an equatorial region. Paper [50] found that frequency transmission over 5 MHz has higher effective data rates because of the fact that mostly man-made noise is centred between 2 and 5 MHz.

Diversity techniques can also be used to decrease fading and improve HF channel efficiency. Frequency diversity, time diversity, antenna (spatial and polarisation) diversity and adaptive beam shaping have been exploited in the early 1930s to remove unwanted multi-paths and they have been introduced in the intercontinental HF radio transmission networks. Nowadays, RF and signal processing devices allow compact and inexpensive realization of complex diversity systems, which greatly reduces the necessary link budget. In order to travel very short distances across the ionosphere, radio waves must be produced almost vertically. Radio waves shall be shot upward from certain angle for continuous coverage of the area around the transmitter, dependent on the scale of the target range. For optimisation of NVIS antennas, knowledge of these elevation angles is required [1].

4. NVIS CHALLENGES, SOLUTIONS AND FUTURE POSSIBILITIES

In this chapter, challenges associated with NVIS operation will be discussed in detail. For a successful operation of a NVIS system, proper knowledge on propagation mechanisms and related parameters is needed in order to achieve optimized system performance. Optimized system performance is possible when the NVIS antenna can transmit and receive strongest signal across the coverage area, hence, improved SNR is realized on receiving the signals. The NVIS propagation mechanism considers elevation angle, fading, noise, as well as polarization as important parameters to use while optimizing the system. Our key objective in this thesis work is to achieve and update information on NVIS antenna, the NVIS propagation mechanisms and the relationship between antenna and propagation. Understanding the processes behind NVIS propagation is vital for enhancing the antenna propagation interface. For a successful NVIS communication, research in ionosphere plays a vital role. Empirical data on ionosphere changing nature is crucial for radio propagation.

4.1. Challenges and Possible Solutions

NVIS uses the ionosphere as a reflector, the transmitted electromagnetic waves are launched at steep elevation angles, typically between 70 degrees to 90 degrees. As all ionospheric radio wave propagation is prone to fading, short term variations result in fluctuations in received signal strength. This fading is caused by multipath propagation and by polarization changes in the ionosphere. Different diversity reception systems have been devised to reduce the fading effect but one of the most recent discovery to cope fading is HF Multiple Input Multiple Output (MIMO) techniques which successfully exploit the multipath aspects of the ionosphere to achieve an increased data throughput or a reduction of the required SNR. Appleton in [18] showed that double echoes from the ionosphere consisted of a pair of characteristic waves reflected by the ionospheric layers. Polarization diversity can be used for improving the channel capacity of wireless communication systems. Two characteristic waves namely, ordinary, and extraordinary waves, have circular polarization with different delays. Here, as two characteristics wave components propagate through the ionosphere, each component follows a different path through ionosphere. If separation between both characteristics wave is sufficiently large, then an improved signal strength is noticed in the receiver. Improved diversity reception can be obtained by the polarization of the antenna to a circular polarization of the characteristic waves propagating in the ionosphere. Significant amount of literature highlighting importance of an ordinary and an extraordinary wave mode for HF MIMO can be found, but more experiments on circularly polarized antennas need to be performed. Based on experiments, [3] with the use of switchable left-hand circular polarization (LHCP) and right-hand circular polarization (RHCP) antenna, an isolation of at least 13 dB was measured between characteristic waves. Further, it was concluded that for HF MIMO, the use of LHCP and RHCP antennas on the transit side and on the receiver side helps to create two very well isolated channels, maximizing MIMO gain.

In emergency situation such as tsunamis, floods, earthquakes, or human-caused tragedies, such as terrorist attacks - cellular, Wi-Fi, or other means of communication system may go down or infrastructure may severely damage. Also, satellite solution is a bit expensive. This could be worse in less developed countries where immediate action or a back-up plan is unimaginable. NVIS propagation is very effective in the circumstances where the distance involved between users is relatively short, but the geography involved is very challenging. In long-distance HF communications, low radiation angles are typically required, which is quite the opposite of NVIS communication where a high take-off angle is required. Some factors limiting the performance of NVIS communication system such as the influence of the ground in close proximity to the antenna, the radiation characteristics of the low dipole antenna, and the propagation medium, are discussed in this section. The NVIS success formula is the selection of an antenna with the required high angle radiation characteristics and an operational frequency that will be refracted back to Earth with no penetration in ionosphere because of which signal might lost in space. The NVIS coverage area is totally dependent on the radiation characteristics of the selected antenna and propagation of the operational frequency through the ionosphere. Once propagation is possible, the targeted received SNR can be achieved by increasing transmitted power or by the cancellation of interference by other measures [32].

The successful prediction of F2 usable frequencies depends on the accuracy of F2 peak parameters prediction, hence limitations to accurate F2 predictions have a cumulative effect on F2 usable frequency predictions. The relationship governing the global distribution of ionospheric parameters are still not completely understood. Further, due to various types of night-time inflation in the F2 layer electron concentration manifest, a night-time F2 layer related prediction may be much less accurate than daytime predictions. So, for predicting ionospheric parameters and F2 usable frequencies, the prediction and casting model recommended in [51] provides successful approach in the prediction of MUF, FOT, time of arrival (TOA), and LUF. The critical frequency is most widely used propagation metric of NVIS. To ensure a non-existing skip zone, the operational frequency needs to be below the critical frequency of F2 layer, thus ensuring continuous coverage from just beyond the LOS up to the distances of a few hundred kilometres. Maintaining 85% of the median MUF is beneficial to estimate the FOT for an NVIS setup. When set, the NVIS channel is not ideal, daytime transmission frequencies less than critical values are subject to higher fading in terms of depth and frequency. During low solar activity, the critical frequency is higher in winter than in summer. Because of increased D layer absorption in summer, path losses are higher than in winter. To ensure full 24-hour operational NVIS capability, frequency agility will invariable will be required, this detracts from the simplicity of the scheme as proposed and has hardware consequences in cost-sensitive situations, particularly if automatic antenna tuning must be executed [28].

A MUF seeking approach should be followed when choosing NVIS operating frequencies to maximize the received SNR with the added advantage of reducing congestion at lower frequencies. To identify MUF, real time channel evaluation is required. For NVIS connection links, ionosondes could be used but ALE is an acceptable method where a bank of channels is sounded in order to find the best quality channel. In recent years, ALE systems have developed to support broadband HF modulation schemes. In case of rapid signal drops, it is wise not to work too closely with NVIS MUF. In addition, it is important to consider wave polarization and antenna orientation so that the amount of frequency margin required can be determined [27], [29].

For the portable and tactical deployment scenarios, compact, low weight antennas are preferred. It is also required that the antenna radiate most of the energy at the elevation angles required by the NVIS communication. Witvliet [3] and [12] determined that the height for maximum NVIS gain is between 0.18λ and 0.22λ above the ground and that for the optimum SNR, the dipole antenna must be 0.16λ above the ground. The vertical radiation angle of antenna increases as it is brought closer to Earth's surface, the electromagnetic constants of soil such as permittivity and conductivity are required for accurate model at the defined operating frequency. It is challenging to determine the required electromagnetic constants with full accuracy but implementing soil moisture technique is beneficial.

Due to different path lengths, the multipath propagation may result in a signal fading because of which the effectiveness of the communication link is reduced. The multipath propagation issue can be solved through the understanding of layer wise propagation based on elevation angle. The achievable ground range is limited by multipath propagation on layer basis. The operational frequency should always be maintained below MUF to avoid skip zone. At elevation angles above MUF, the signal gets lost in space. Further, an operational frequency considerably lower than FOT results in reduced ground range. Another important performance limiting factor for NVIS operation is solar activity. Critical frequency is measured based on solar activity feedback to determine effective FOT. At defined FOT, raytracing of ground distance is possible considering elevation angle from 0 degree to 90 degree [32].

For radio receivers, the lower reception threshold is generally determined by radio noise (natural and man-made noise). Natural noise is caused by the atmospheric discharges and radiation from extra-terrestrial objects and man-made noise by unwanted emissions of electronic equipment and electrical machinery. Both noise vary with frequency and time, so local radio noise measurement reference is always helpful for HF radio link planning as well as to provide electromagnetic compatibility (EMC) feedback. Identifying the deficiencies and merits of HF noise measurement antennas is always beneficial to make an antenna less dependent on the ground constituency and to improve the low angle responses of the antenna.

4.2. Future Research Aspects

The subjects discussed in this thesis have contributed to the understanding about the ionosphere and its behavior, propagating component and NVIS antennas. During the literature review, new research questions have arisen that could be the future research topics. Examples of topics deserving further study in the future have been established in following study.

- NVIS antenna: Various types of NVIS communication system antenna operations are discussed in Section 3.2.2. It will be beneficial to expand research into the effect of antenna height on diverse NVIS communication performance. For several antenna types, for multiple coverage area sizes combined with its ideal dimensions and installations heights for multiple types of soil, NVIS antenna gain and NVIS guidance simulations using software defined radio (SDR) could be achieved. This will provide a valuable point of comparison for the selection of NVIS antennas. The use of active antenna arrays could further improve the SNR and, at the same time, eliminate interference in the co-channel by removing signals that arrive at a low elevation angle in the NVIS reception. As was the case in [52], the efficiency of dual circular polarized systems could be improved independent of geomagnetic latitude and immediate propagations through experiments with adaptive polarizations to achieve the maximum channel separation.

- NVIS propagation: Further analysis is necessary to identify the physical paths that induce the usual multipath fading on the NVIS channel even though one of the characteristic waves is excited and only F2-layer propagation occurs. This is important in order to identify the source of fading that is required in order to implement steps to minimize this fading. To explain its existence, additional night-time experiments are needed over MUF propagation over short paths.
- HF NVIS mesh networks: Based on the HF mesh network design, some future research issues require further considerations, including the possible conflict between several traffic streams running through the mesh, a fitting creation of routing protocol and a multi-cast routing protocol in the military applications of HF mesh networks.
- NVIS channel simulation: It would be invaluable to compare reported channel data from actual NVIS transmission under a wide range of propagation conditions in a practical yet repeatable way. Studies to transform documented real-life propagation into a practical F2-layer and E-layer NVIS propagation channel simulator will help compare and optimize modulation, coding, and diversity protocols. These simulations can involve both independently and in conjunction ordinary and extraordinary wave channels.
- Modulation systems for NVIS channels: Optimized modulation schemes for two characteristic orthogonal wave channels must be applied and evaluated on the same frequency with reduced coding overhead. Objective comparisons of many standardized HF communication protocols over identical NVIS channels is desirable. The key consideration is to establish the strongest and most efficient HF radio communication protocol.
- Radio noise: For remote sensing and the IoT, many physical layer solutions have been developed in recent years. There are regions that are not served by mobile operators. Both NLOS and large coverage are given by the NVIS activity. Thus, an NVIS-based approach may be configured for remote sensing.
- HF link throughput using wider bandwidth: The analysis of the HF-channel impulses in broadband offers data on characteristics, such as number of propagation modes, signal flight time, Doppler shift, frequency dispersion, dispersion of time, fading figures, signal power, noise and interference. Study into these criteria allows to design channel models for networks.
- HF MIMO NVIS: HF data rates are excessively low based on modern communication demands. By applying higher order constellations and efficient forward error correction (FEC), it is likely to increase data

rates. The increased data rates result only under extremely high SNR conditions. Due to variability of HF channel in NVIS case, gaining high SNR conditions is not always feasible. Multiple-input multiple-output approach enables increased link reliability, robustness to interference with low energy consumption. So, MIMO HF NVIS shows a promising research area in order to exploit both diversity as well as spatial multiplexing by applying adaptive processing. There has been noticeable research to study feasibility of HF MIMO for NVIS links but with limited antenna and polarization configuration. So, with different antennas as well as polarization approach the performance metrices can be determined for NVIS operations.

- Automatically reconfigurable NVIS system: One research approach could be to test the feasibility of the NVIS communication system to a remote sensing scenario. The idea is to deploy sensors within hundreds of Km away from the transmitter without any communication infrastructure. So, with this low-cost software defined radio (SDR) approach, channel sounding, modulation scheme testing, and power consumption analysis as well as useable frequency based on the weather conditions can be determined. In this way, an optimized antenna selection scheme for narrowband frequency can be determined in order to have high antenna gain which results in low transmitted power. In this way, a low cost SDR platform can be designed for low power consumption, which can be applied for remote sensors, emergency rescue, and communication in developing countries. Additionally, with SDR approach, an automatically reconfigurable network design is possible to select parameters based on feedback from the ionosphere measurements and predictions as well as receiver feedback. Based on designed feedback SDR and with the novel concepts from artificial intelligence (AI) and machine learning, an optimized overall system performance can be achieved.

5. DISCUSSIONS AND CONCLUSIONS

Communication is an important part of our life. The communication technologies can be categorized based on the used radio frequency range. Frequency range of 2 – 30 MHz has been classified as high frequency radio. The objective of this thesis was to study and report on feasibility of using NVIS technology in various critical applications. To that end, we try to exploit concepts of HF communication along with ionospheric wave propagation, which are very important to understand and develop NVIS systems. We developed a basic understanding through an extensive literature review on NVIS systems. We aimed to carry out this study in such a way that a wide range of readers (students, professional or non-professional) can understand the basic principles of NVIS communications. Even though it is not possible to deal with all the elements related to NVIS systems in great depth in this thesis, the most important aspects of NVIS systems are presented and discussed. Mathematical interpretation is included only when there is need to illustrate key issues. High frequencies (2-30 MHz) can be utilized to establish long distance communication links via the ionosphere. HF links between transmitter and receiver can be established via line of sight (signal has unobstructed link between transmitter and receiver), groundwave (that covers relatively shorter range), as well as skywave (long distance communication). In an HF system, the transmitting station consists of a transmitter matching network and antenna. From the transmit antenna, for short-range communication a high-angle wave propagation is needed, while for long-range a low-angle propagation is needed.

The ionosphere is composed up of ionized particles in Earth atmosphere and plays a vital role in the propagation of radio waves. It contains ions and free electrons and extend from altitude of 60 Km to more than 400 Kms above the Earth surface. The free electron makes the ionosphere nature continually changing over time and affects the propagation of waves. Hence, the ionosphere plays a significant role in HF communication. There are several technical as well as operational advantages of using NVIS system. NVIS transmission occurs utilizing lower HF frequencies (2 MHz - 10 MHz) and high take off angle (75 degree or more). In NVIS operation, if transmit antenna is optimized for high angle radiation, the receiving waves will arrive at high angle from the ionosphere. The resultant communication utilizing NVIS will be more robust and reliable as compared to traditional skywave. Due to this high take off angle, the transmitted signal reflects back to the Earth, covering regions of up to several hundreds of Km away from the transmitter as well as providing coverage in hilly and mountainous regions. A line-of-sight propagation is established from the transmitter to the ionosphere, and another from the ionosphere to the receiver. A shorter overall path is maintained between transmitter and receiver, results in less attenuation. Therefore, NVIS does not require infrastructure such as satellite or repeaters. Reliable communication can be established between transmitter and receiver with relatively low transmit power. NVIS can cover zones which are too far for groundwave propagation, and not yet far enough to receive skywaves reflected from the ionosphere. In this way, NVIS propagation can supress fading caused by multipath. So, NVIS technique can reduce noise and interference, which results in an improved SNR. NVIS works on certain range of HF system, so choosing an effective operating frequency is essential for the correct operation of the communications system. In NVIS operation, the selection of operating frequency is primarily a function of time and solar activity. Time of day, sunspot activity, type of antenna used, atmospheric absorption, as well as atmospheric noise should be considered. A variety of antennas can be used in vertical or horizontal configuration. Both transmitting and receiving antenna must be optimized for NVIS operation. The transmit antenna must be optimized to provide maximum gain so that maximum energy is concentrated towards the elevation angle. In similar way, receive antenna must be optimized in such a way that it identifies and accept strongest beam and supress fading. Overall, the infrastructure-free approach of NVIS is highly attractive for disaster relief communication.

It is well known that fourth generation (4G) and fifth generation (5G) systems are implemented worldwide, and more research target are set by industries as well as researchers to jump into higher frequency communication bands. So, based on this wide research possibility, research focus cannot ignore the concept of next generation HF communication where MIMO, artificial intelligence as well as machine learning approaches can update the standard HF communication system model into an intelligent and wideband system.

There are many areas in the world lacking internet connectivity resulting in a clear digital divide. Recent estimations show that as many as 2 billion people worldwide remain unconnected. As a result, human well-being as well as economic development in challenging areas are affected severely. For these areas, there is a need of affordable systems that can provide at least basic connectivity so that the digital divide gap can be bridged to some extent. The recent vision of 6G [6], [7] provides a depth insight on the digital divide by discussing the requirements and challenges followed by research topics that must be tackled by 6G. The United Nations sustainable development goals (UN SDGs) set a number of objectives on the global challenges including climate change, poverty, and inequalities. These issues can be overcome by considering the following factors: human well-being and capabilities obstacles, urban development, global environmental commons, sustainable and economics, food system and nutrition pattern, energy decarbonisation and universal access. On the other hand, 6G communication opens an era where connected people, things and intelligence is possible.

Both 6G communication system and UN SDGs are targeted to be achieved from 2030 on, aiming to enhance global growth and productivity, create new business models, transforming many aspects of society by framing opportunity and challenges of a desirable future world, and covering topics as broad as ending poverty, gender equality, climate change, and smart cities. Data rates improvements have been rapid with different generations of radio mobile technology, still remote and rural areas lacks basic wireless connectivity. So, one motto of ‘connected society’ should be set and fulfilled within some specified time. The internet connectivity has direct relation to the state of education, health, agriculture, industry, transportation, and employment. On the basis of the above-mentioned sectors, individual, then society, then nation, and then whole world economic as well as social transformation is possible. Providing remote connectivity with 6G technologies needs to be done in a cost attractive manner to the whole stakeholder chain, the equipment manufacturer, the service provider and the end users. A new type of resource optimization is necessary in both power grid and communication systems. The HF NVIS approach is a possible future solution for providing remote areas networking along with satellite solutions. The benefit of HF NVIS in communication resilience as it can fulfil connectivity requirements with non-terrestrial platforms. Further, energy-efficient connectivity can be achieved with HF NVIS by deploying non-terrestrial nodes on demand, implementing smart duty cycle control mechanism, and thus reducing management as well as operational cost.

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